MODELING, SIMULATION AND CONTROL STRATEGY FOR MICROGRIDS

By

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MODELING, SIMULATION AND CONTROL

STRATEGY FOR MIRCROGRIDS

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Abstract: The traditional centralized bulk transmission network of high voltage and long distance has some shortcomings, such as power quality, safety, reliability, economy and flexibility. To survive and develop, people need more and more energy. As the traditional energy sources, such as coal, petrol, gas and other fossil energy resources, being exhausted in the next 100 years, the renewable energy technologies, like solar, wind, tide, geothermal, etc. has been developing rapidly. The best way to utilize the renewable energy is to build a small local grid, which consists of several energy sources and local loads, named as microgrid. The microgrid can operate in two modes, grid-connected mode and island mode. In the grid –connected model, the microgrid will exchange the power flow with utility grid. When emergency comes up, to improve the reliability and stability, the microgrid will be operating in island mode. After the disturbance, the microgrid will reconnect to the utility grid. Based on different characteristics of microsources and microgrid, this thesis sets up a microgrid model with several microsources, including direct-drive wind power system to make maximum use of wind power, which uses battery and hydro as backup. This model applies to the area with sufficient wind and water energy. To ensure the power supply to sensitive load, how to keep the power balance is the most crucial factor. This requires coordinated control strategy. Aiming at reliable power supply and maximum use of renewable energy, this thesis uses a control strategy based on state transition of microgird.

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CHAPTER I

INTRODUCTION

1.1 Background and meaning

With the development of global economy, the electricity demand increases rapidly. The power generated by electricity utility mostly relies on traditional resource, such as coal, hydro and nuclear. The fossil resource takes a large portion in generating power. With the consuming of the fossil fuel, energy crisis comes to the front stage. The survey about the energy reserve at the beginning of 21st century indicated that the petrol reserve would be exhausted in 40 years, the natural gas would be used up in 60 years, and the coal would last 220 years [1]. The data tells people fossil fuel is so limited, and people need to find out new way to generate power. Also, the large use of fossil fuel is one of the main reasons that global environment becomes worse and worse. The CO_2 and SO_2 caused by combusting fossil fuel strengthen the greenhouse effect and acid rain. In the 21st century, people are facing the challenges of economy and sustainable development. Under the circumstance of limited resources and environment protection, it requires people to find the renewable energy to replace the traditional energy resources. Using renewable energy, like wind, solar and etc. becomes the only way to realize the sustainable development for human society. In the recent years, solar energy and wind power are hot issues between the specialists and researchers. Research and practice illustrates that solar radiation is widely spread on earth, renewable, environmental friendly. The solar energy is considered as a perfect method to replace fossil energy [2].

The centralized bulk transmission network is the main method to generate, transmit and allocate the power in the world. It supplies more than 90% load right now. However, it has some disadvantages: the first one is that it cannot track the load change. In the summer time, the load of air conditioners increases sharply, which would cause the shortage of power. But due to the low usage in other time, building utility for this kind of load is not reasonable. The second disadvantage is that in the large-scale transmission network, the local fault will easily spread to cause a tremendous blackout in a large area. The most famous example is Northeast blackout in 2003. A software bug in Ohio leads to a blackout, which affects more than 50 million people. It exposed the vulnerability of the large-scale network. Because of the advantages of less pollution, high reliability, high efficiency, and flexible location, the distributed generation (DG) solves several potential problems of large centralized network. As a solution to connect DG into utility grid, people proposed a concept of microgrid. The microgrid combines generators, load, storage, and control components as a single self-controllable entity, supplying electricity to users. The generators in microgrid are mostly mircosource (less than 100kW), such as micro gas turbine, fuel cell, solar cell, and wind turbine. Microgrid can operate in two modes, grid-connected mode and island mode.

1.2 Description of microgrid

According to Department of Energy (DOE), microgrid is a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously. Consortium for Electric Reliability Technology Solution (CERTS) also provides a definition of microgrid,.The main characteristics of CERTS microgrid are plug and play, and peer-to-peer[3]. The plug-and-play concept means that a distributed energy resources unit can be placed at any point within the microgrid without re-engineering its controls. The plug-and-play functionality is similar to the flexibility one has with home appliances. That is, just as an appliance can be plugged in wherever there is an outlet, one can similarly locate distributed energy resources units at any location within a facility or building where they might be most needed. The peer-to-peer concept insures that no single component, such as a master controller or a central storage unit, is required for operation of the microgrid. Therefore, by its very design, the CERTS Microgrid can continue operating with loss of an individual component or generator. (With one additional source, (N+1) it can insure even higher levels of reliability.)

According to the demand of power market, supply safety and environment factors, Europe proposed a plan, named as 'Smart Grid' [4]. The plan pointed out that the future European transmission network would have some characteristics:

1. Flexible: fulfill users' diverse demands
2. Reliable: increase power supply reliability and security to fulfill the demand in digital era
3. Economic: by technology innovation, energy management and market competition, increase the power network economic efficiency.

As people can see the development and research of microgrid is not revolution or challenge to the traditional centralized, large-scale network, but a beneficial supplement by providing high efficient, environmental friendly power to utility grid.

The typical frame of a microgrid provided by CERTS is shown in Fig 1.1.

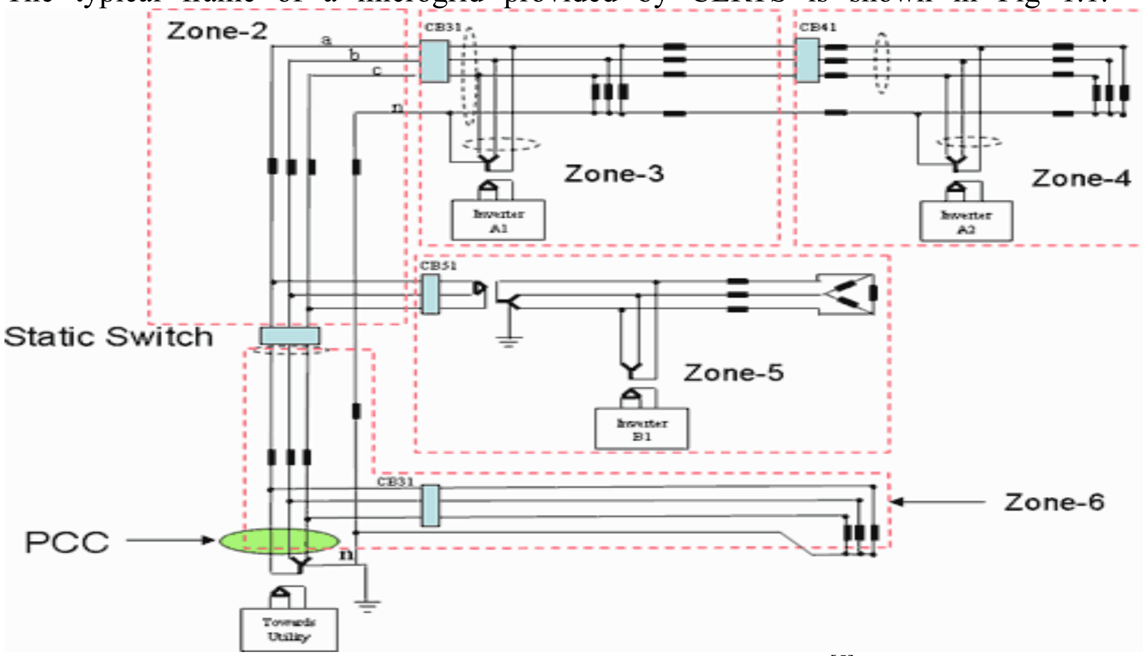

Fig. 1.1 a typical frame provided by CERTS [5]

Microgrid has two operation modes: grid-connected mode and island mode. In the regular situation, microgrid connects with the utility grid by PCC (point of common coupling). While the power generated by microsources is less than the loads in the microgrid, microgrid absorbs energy from main grid to keep the power balance. While the power generated by microsources is larger than the loads, microgrid gives out the extra power to utility grid. So, in the grid-connected mode, the power flow is dual directions. When fault occurs in the utility grid, PCC breaks up. The microsources and loads keep the power balance to operate in island mode. After the fault clear, microgrid would reconnect to the main grid.

Due to various geographical and climate conditions, microsources are different in different places. Some places are only suitable for one microsource, meanwhile some other places may combine two or three microsources. And the loads on different microgrids are not the same. To keep the power balance in the microgrid, people need to research on how to coordinate microsources.

Microgird is a system including loads and microsoureces. It can supply both power and heat. The power electronic applications convert power to meet the load requirement. They also provide necessary control. Microgrid is considered as a single controllable entity and will fulfill users' demand of power quality and supply security.

Most microsources are distributed generation, such as photovoltaic, wind turbine, micro gas turbine and small hydro system. The microsources are weak in instantaneous power tracking, and inverter can provide little storage. In the island mode, if add loads suddenly without adding storage, the actual power of microsources would not meet the load demand. It would lead to voltage drop at the load. Another situation, when switching from grid-connected mode to island mode, microsources could not increase power rapidly in the switch process to meet the load demand. Different from traditional network, to keep stability, most microgrid has storage components. Storage components are crucial part of microgrid, which do not exist in traditional network. Mostly used storage components are flywheel, battery and super-capacity.

The United States first proposed the definition of microgrid, and also the one with most authority. The microgrid proposed by CERTS is based on power electronics technology and the microsource and load are less than 500kW. By using power electronics technology, CERTS came to the ideas plug and play and peer-to-peer [4]. So far, the research conducted on the CERTS test bed successfully examined the model, simulation, protection and control strategy and economic benefit. From the test bed, how to increase the reliability, meet the various demand, decrease the cost will be most important direction in the future.

Microgrid is flexible in operation mode and has high power quality. But it cannot be separated with sophisticated and consummate control system. Control strategy is also a difficult point in microgrid research. So far, there are three microgrid control strategies:

1. ‘Plug and Play’ and ‘peer-to-peer’ control method based on power electronics technology [11]

This control method uses the droop characteristics curve as commonly used in traditional generators to allocate the power to different generators to keep balance. But this method doesn’t consider voltage and frequency recovery. It may affect the frequency quality.

2. Control strategy based on power management system [[12]

This method controls the active power and reactive power of every control modules to meet the frequency demand. To fulfill the different reactive power demand, power management system uses several control methods to improve the flexibility and performance.

3. Control strategy based on multi-agent technology [13]

This method applies the multi-agent technology used in the traditional power system to microgrid control system. This method provides a system embedded with control functions, but without managers. The weak point of this method is obvious. The multi-agent technology is now used in coordinating market and managing power. To be further adopted into the voltage and frequency control, there is still a lot of research. When the loads or structures changed, how to coordinate all the distribution generators to insure that the microgrid will meet the power quality for the loads under different operation modes is the key point of reliability. In the real microgrid system, people will use different control strategies to control different DGs. For the power like micro gas turbine and fuel cell, it is easy to control at given active power and reactive power. And it is also easy to use V/f control. The fuel cell will insure the stability of frequency and voltage. But for the power like wind turbine and solar panels, the power output is affected by the weather. They are obviously intermittent. To keep fixed power output, it will need large capacity storage. In this case, the target is to make most use of renewable energy. Usually, PQ control strategy is adopted here.

1.3 Work in this thesis

This thesis first introduced the definition, structure, operation modes and characteristics. Then summarized the control strategies of microgrid. In Chapter II, this thesis analyzed the problems of wind turbine in the microgrid, set up a model including wind turbine, battery reserve and hydro, and set up the model of microsources separately to form the microgrid structure. Then considered the control strategies of microsources. From different combination of microsources, this thesis drew the state transition chart. At last, this thesis talked about the control strategy based on power and load management and simulated some main operation states and state transitions.

The main work is listed below:

1. Summary of microgrid concept, structure, operation mode and characterics
2. Analysis of the effect of intermittence in wind turbine, model structure with wind turbine, battery and hydro
3. Analysis of different microsources combination and state transition
4. Control strategy based on power management and load management
5. Simulation in PSCAD to verify the state transition and reliability of the control strategy.

CHAPTER II

MODELING AND CONTROL ANANLYSIS OF MICROSOURCES

Microgrid consists of microsources, loads, storage, and control systems. Wind energy is most widely used renewable energy around the world.

Maximum power point tracking technology is adapted to control the wind turbine generation. The power of wind turbine is directly determined by the wind speed. The wind speed is not a constant value due to the time and weather factors, which means that the power output of wind turbine will change according to the wind speed. When disconnected with utility grid, the change and instability of wind power will lead to frequency shock, even the collapse of the whole microgrid.

Because of the intermittence of wind power, the microgrid in this thesis uses hydro and wind mix as supplement. To fulfill the fast response, this thesis introduces the battery to support instantaneous power. When connected to the utility grid, the frequency will be supported by utility grid, and battery will be used to adjust the voltage change caused by wind generation. When microgrid is under island mode, the microgrid uses battery and hydro as main units to keep the voltage and frequency.

This thesis illustrates the mixed wind, hydro, battery microsources. Wind turbine generator uses variable speed constant frequency direct-driven wind turbine generator, which reduces the maintenance work by not introducing gearboxes. The hydro system will use a 5MW generator. To simplify the analysis, a DC voltage source will be used as a storage battery, without considering the charging and discharging process. The model of wind turbine, battery and hydro will be listed below:

2.1 Model of wind system

For all kinds of renewable energies, wind energy is most rapidly developed one, because of large capacity and environment friendly. Since the change of actual wind speed, the output of direct-driven generator is not stable. It needs rectifiers and inverters to transform into constant voltage constant frequency AC power to the grid. Direct-driven wind generator is mainly made up of wind turbine, direct-driven synchronous generator and converters.

2.1.1 Model structure

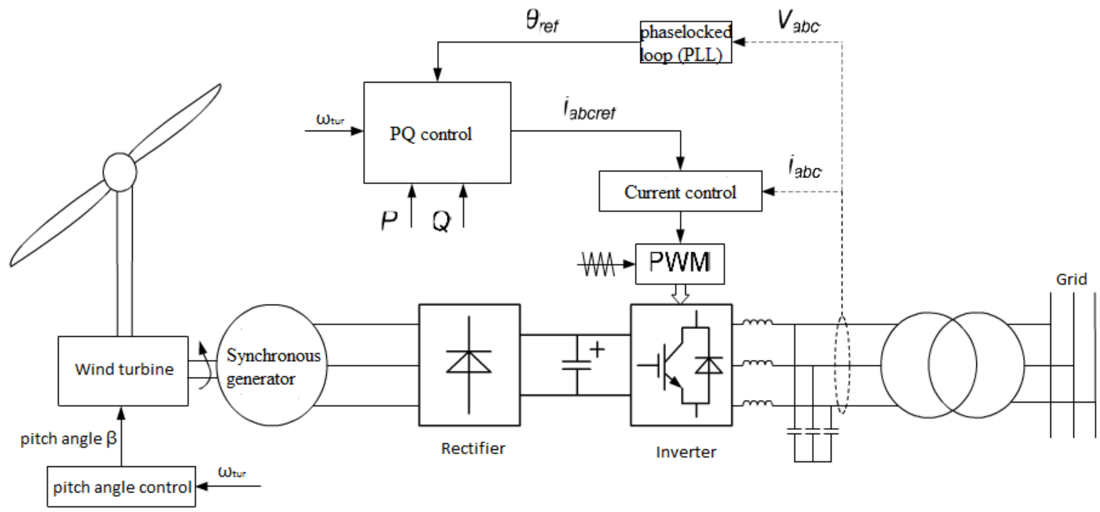

Fig 2.1 Principle of direct-driven wind generation system

The principle of direct-driven wind system is shown in Fig 2.1. This system consists of variable pitch wind turbine, direct-driven synchronous generator and controlled power electronics converter and etc. The converter contains diode bridge rectifier and 6 IGBT inverters. The principle of direct-driven wind generation system is that variable pitch wind turbine directly connects with rotor of synchronous generator. After uncontrolled inverters and capacity filter, the output becomes DC and reaches the voltage requirement of inverters. Then transfer the power to grid. The inverters are in charge of adjusting active power and reactive power. In the DC-to-AC process, there will be lots of harmonics. Then, there is LC filter between inverter output and grid to reduce harmonics.

Model of wind speed

Wind turbines reply on wind. Wind speed directly determines the dynamic characteristics of wind turbines. Generally, wind speed model have 4 components: mean wind V_{mean}, gust wind V_{gust}, ramping wind V_{ramp}, random wind V_{noise}, the input wind speed can be described as,

$$V_{wind} = V_{mean} + V_{gust} + V_{ramp} + V_{noise} \tag{2.1}$$

Model of wind turbine

According to aerodynamics characteristics, the blade torque is shown as below:

$$\lambda = \frac{\omega_{tur} R}{V_{wind}} \tag{2.2}$$

$$P_{tur} = \frac{1}{2} \rho \pi R^2 C_p V_{wind}^3 \tag{2.3}$$

$$T_{tur} = \frac{P_{tur}}{\omega_{tur}} = \frac{1}{2} \rho \pi R^5 C_p \frac{\omega_{tur}^2}{\lambda^3} \tag{2.4}$$

λ is tip speed ratio. ω_{tur} is rotating speed. R is blade radius. V_{wind} is wind speed. P_{tur} is mechanical output power. ρ is air density. C_p is power coefficient. T_{tur} is output mechanical torque. In this thesis, C_p can be expressed as [14],

$$C_P(\lambda, \beta) = 0.22\left(\frac{116}{\alpha} - 0.4\beta - 5\right) e^{\frac{-12.5}{\alpha}} \tag{2.5}$$

$\frac{1}{\alpha} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$, β is blade pitch angle.

The blade pitch angle of direct-driven wind generator uses in this thesis is variable. Controlling the blade pitch angle is a way to control the input power. From 2.5, when β is zero, C_p is max. So it needs to keep β zero at the rated wind speed,

Model of direct-driven generator

The stators direct axis voltage and quadrature axis voltage equations of direct-driven synchronous generator are shown as 2.6.

$$\begin{cases} u_{ds} = -r_s i_{ds} + \omega_{gen} x_q i_{qs} \\ u_{qs} = -r_s i_{qs} - \omega_{gen} \left(x_d i_{ds} - \psi_f \right) \end{cases} \tag{2.6}$$

Equation of rotor motion is

$$\begin{cases} \dot{\omega}_{gen} = \dfrac{T_{gen} - T_e}{2H_m} \\ T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \end{cases} \qquad 2.7$$

Stator flux linkage equation is

$$\begin{cases} \psi_{ds} = -x_d i_{ds} + \psi_f \\ \psi_{qs} = -x_q i_{qs} \end{cases} \qquad 2.8$$

u_{ds}, i_{ds} are stator direct axis voltage and current. u_{qs}, i_{qs} are stator quadrature axis voltage and current. r_s is stator equivalent resistance. x_q is stator quadrature axis reactance. x_d is stator direct axis reactance. ω_{gen} is rotating speed of rotor. ψ_f is rotor flux linkage. T_{gen} is generator mechanical torque. H_m is inertia time constant. ψ_{ds} is stator direct axis flux. ψ_{qs} is stator quadrature axis flux.

Model of wind generator convertor

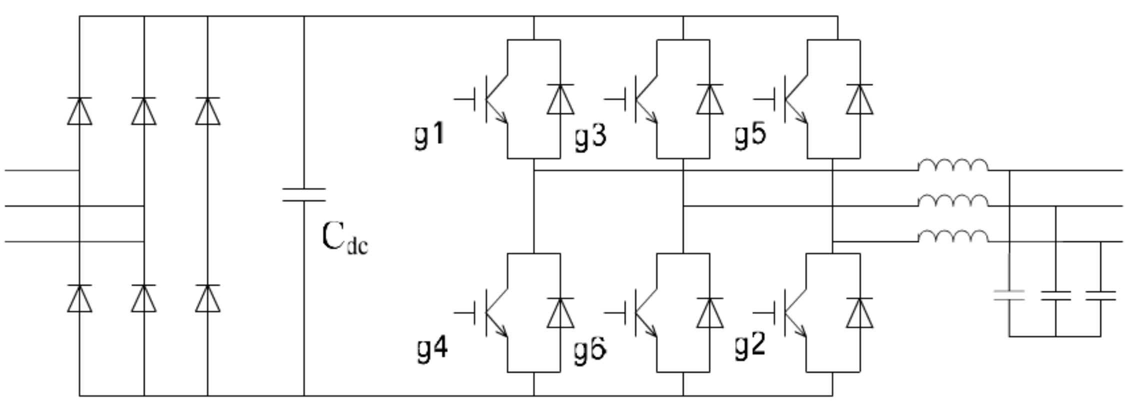

Fig 2.2 Topology of wind generator convertor

The front part is uncontrolled rectifiers to transfer AC to DC. Then after inverters, DC voltage changes to AC voltage. In this structure, 6 diodes make up uncontrolled rectifier. Then, 6 IGBTs make up a voltage source inverter (VSI). The latter part adopts LC filters to reduce harmonics.

Model of shaft

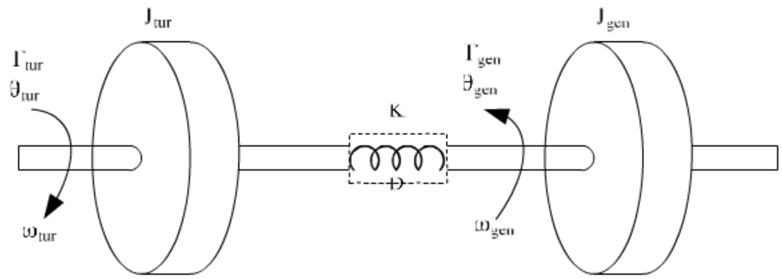

Fig 2.3 Model of shaft

Wind turbine directly mechanical connects to the generator. The two equivalent masses model fully illustrate the dynamic characteristics between wind turbine and generator (eliminate the self damping). This model also shows the interrelationship between wind turbine and generator.

The equations of mechanical connection:

$$\begin{cases} 2H_{tur}\dfrac{d\omega_{tur}}{dt} = T_{tur} - k\theta_s - D_{tur}\omega_{tur} \\ 2H_{gen}\dfrac{d\omega_{gen}}{dt} = k\theta_s - T_{gen} - D_{gen}\omega_{gen} \\ \dfrac{d\theta_s}{dt} = \omega_0\left(\omega_{tur} - \omega_{gen}\right) \end{cases} \tag{2.9}$$

H_{tur} *and* H_{gen} are inertia constants of wind turbine and generator. K is stiffness coefficient between two masses (kgm^2/s^2). D_{tur} *and* D_{gen} are self damping coefficient of wind turbine and generator stators (Nm/rad).θ_s is relative angular displacement between two masses (rad). T_{tur} *and* T_{gen} are mechanical torque of wind turbine and electromagnetic torque of generation. ω_{tur} *and* ω_{gen} are rotating speed of wind turbine and generator rotor.ω_0 is synchronous speed.

2.1.2 Control strategies

To make most use of renewable energy, the wind turbine generation uses PQ control. By controlling the output inverters to get maximum active power output. To control the reactive power, it uses constant power factor control to make sure that the output reactive power is constant. There are two control methods.

1. Maximum power point tracking

Under the rated wind speed, to get most wind energy, it requires to change wind turbine speed but keep optimum pitch $\beta = 0$ so that the active power output of wind turbine changes with wind energy. Fig 2.4 is the output power characteristics curve under different wind speed. As shown in Fig 2.4, the optimum power curve is the line of all the optimum working point P_{turmax}, When wind speed is constant, different rotor speeds give out different power output. By controlling rotor speed, the wind turbine generator will produce maximum power output.

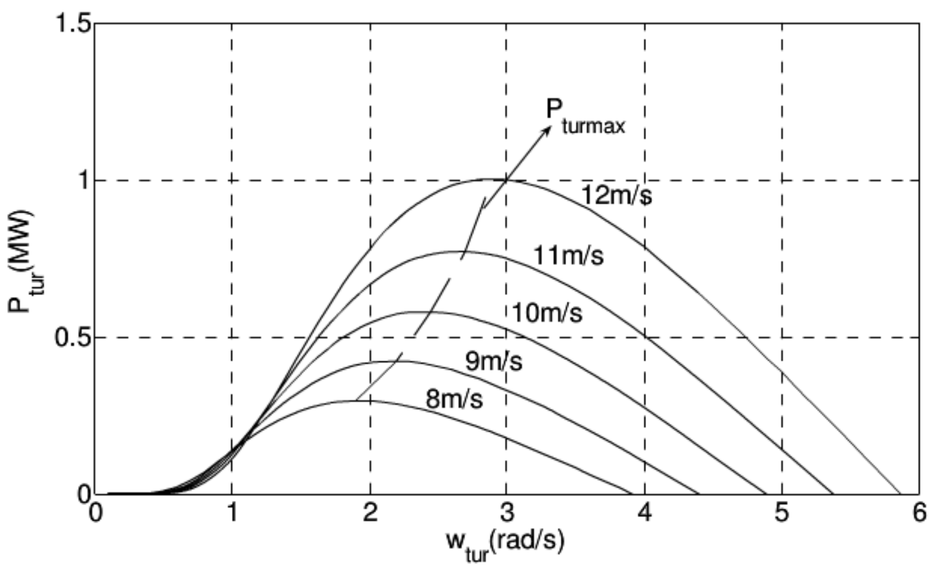

Fig 2.4 Power characteristics curve under different wind speeds

2. Variable pitch angle control

When wind speed increases to make the generation output near the rated power, due to the restriction of wind turbine, it requires that the rotating speed and output keep near the rated number. Increasing pitch angle may lead to significant decrease in wind energy usage; also decrease to generator output power. When wind speed is larger than the rated wind speed, the system will use variable pitch angle control. By changing the pitch angle, the system is able to control rotating speed and output power. The model is shown as Fig 2.5. When rotor is working under the maximum speed, control switch S_c is at W_{max}, the pitch angle is zero. When rotor speed is larger than the maximum speed, the system increases pitch angle to keep the generator output near the rated power.

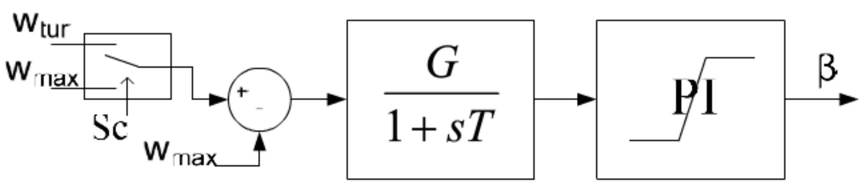

Fig 2.5 Variable pitch angle control structure

2.2 Battery reserve and DC-AC transfer

2.2.1 Model structure

This thesis introduces DC voltage source as battery reserve, without considering charging and discharging process. When ‘wind + battery + hydro’ microgrid connected with utility grid, the frequency is supported by utility grid. The battery reserve is only used to adjust active power and restrain the voltage change caused by active power change from wind turbine. When microgrid is under island operation, hydro units will be the main unit and use Droop control. The battery unit uses PQ control to compensate the active power provided by wind turbine. The Fig 2.6 shows the structure of battery reserve:

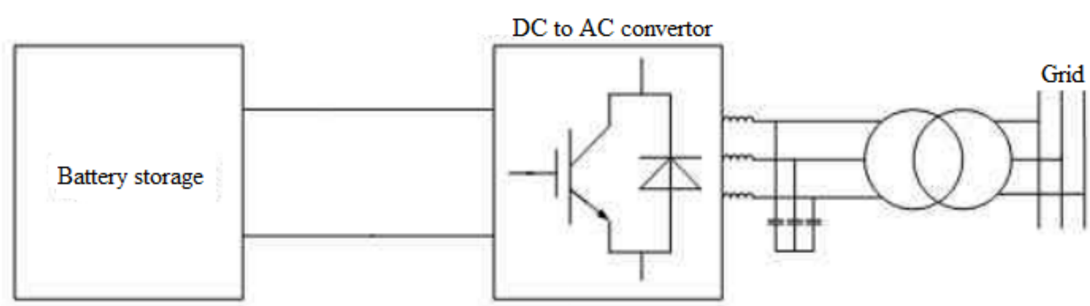

Fig 2.6 Model structure of battery reserve and DC-AC inverter

2.2.2 Control strategy

P/f and Q/V Droop control

The inverter output voltage is 1.95kV. In this voltage line, the unit resistance is much less than unit reactance (R<<X). The frequency relies on active power and voltage relies on reactive power. Resistance can be eliminated, when power angle δ is small, the power transmission equation is listed below:

$$P = \frac{U_1 \cdot U_2}{X} \cdot \delta \tag{2.10}$$

$$Q = \frac{U_1^2}{X} - \frac{U_1 \cdot U_2}{X} \tag{2.11}$$

From 2.10 and 2.11, the voltage drop (U_1-U_2) is determined by reactive power Q. Power angle δ and frequency f mainly depends on active power P. In the 'wind + hydro + storage' microgrid, when battery is the main control unit, the microgrid will use P/f and Q/V Droop control strategy.

2.3 Model of hydro system

Same as wind energy; hydro energy is also a kind of renewable and environmental friendly resource. Hydro generation system mainly includes hydraulic turbine, synchronous generator, governor (speed controller), and exciter. Hydraulic turbine transfers hydro energy to mechanical energy. Then synchronous generator transfers mechanical energy to electric power. The hydraulic turbine governor is in charge of power and frequency control. The exciter controls the output voltage amplitude.

2.3.1 Model structure

The hydro generation system structure is shown as Fig 2.7.

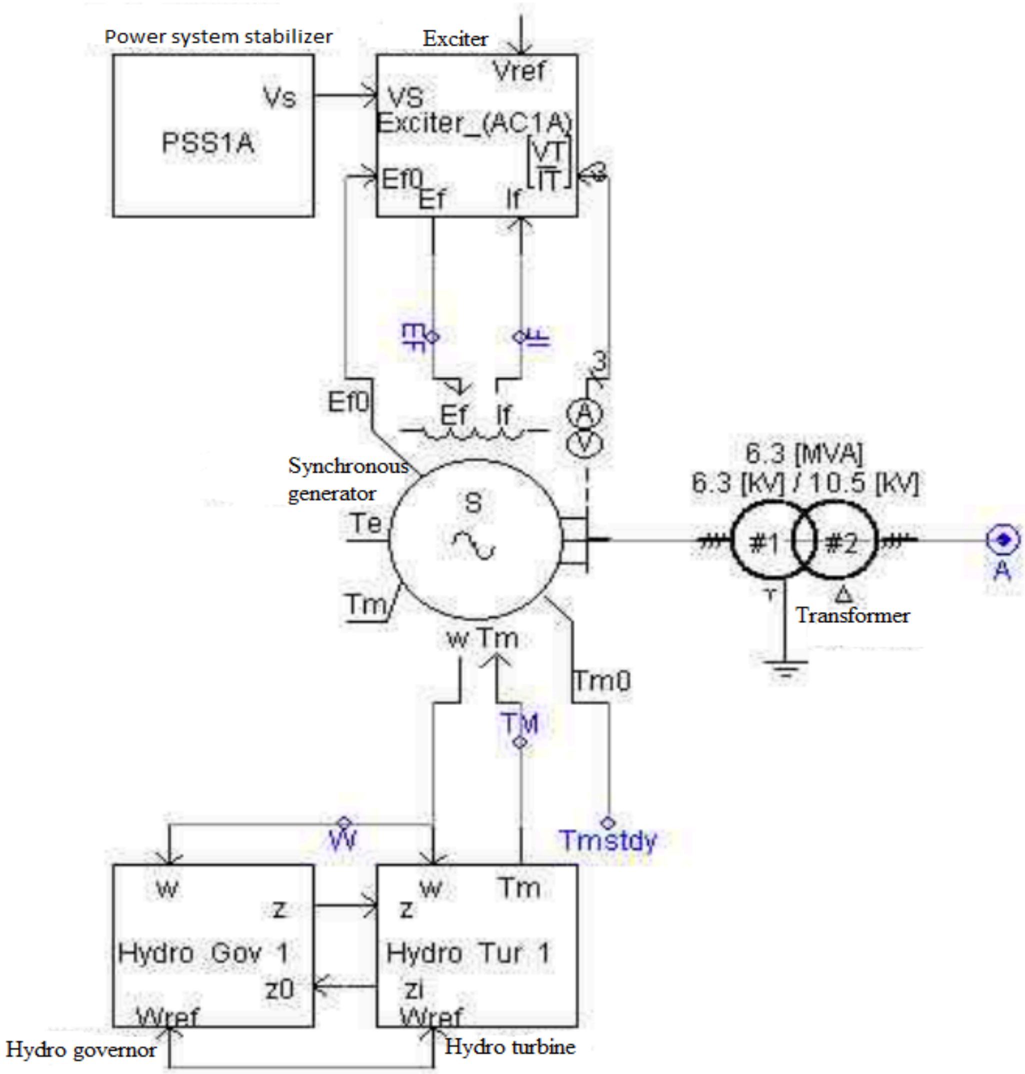

Fig 2.7 Structure of hydro generation system

The Fig 2.7 contains a 5 MW synchronous generator (s), hydro turbine (Hydro Tur 1), hydro governor (Hydro Gov 1), power system stabilizer (PSS1A), exciter (Exciter_ (AC1A)), and transformer. The hydro turbine transfers hydro energy to mechanical energy, then rotates the rotor to generate electric power. Hydro governor control the speed of hydro turbine. By controlling the field current, the exciter guarantees the synchronous generator output changing in a continuous volume to keep voltage stable. The power system stabilizer adds the damping to rotor oscillation to increase reliability.

2.3.2 Control strategies

The control models mainly include model of hydro governor and synchronous generator exciter.

It is hydro governor's responsibility to keep frequency and load balance. In order to control the hydro turbine speed, the hydro governor controls the guide vane angle to restrain the water quality. Mechanical hydro governor is related as a PI regulator. The model is shown as Fig 2.8.

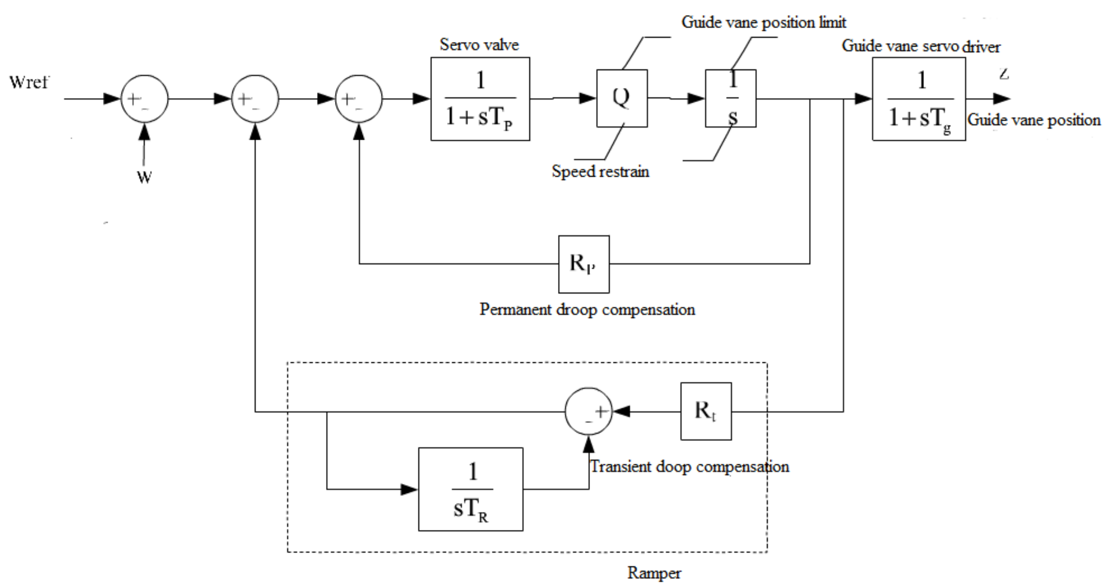

Fig 2.8 Model structure of hydro governor

In the Fig 2.8, Q is servo gain [p.u.]: R_p is permanent droop compensation [p.u.]; R_t is transient droop compensation [p.u.]; T_g is main servo time constant [s]; T_p is servo driver time constant [s]; T_R is reset time constant [s]. The restrain is maximum guide vane location is 1, and minimum guide vane location is 0.

As shown in Fig 2.8, the system compares the rotating speed signal from sensor with rated rotating speed. Then combines the difference between actual and rated rotating speed, permanent droop compensation signal, and transient droop compensation signal. The combined signal is transferred through servo control gate, speed limit gate, and guide vane location restrain gate to control the guide location. However, water is almost a incompressible material. If the guide vane closes too fast, the water pressure may collapse the waterlines. To prevent the fast close, there is a damper providing transient droop compensation.

The basic function of exciter is to provide DC current to synchronous generator field winding. By changing the field voltage, the field current will change accordingly. This thesis adopts the IEEE standard module AC1A exciter system. The Fig 2.9 shows the structure of exciter system.

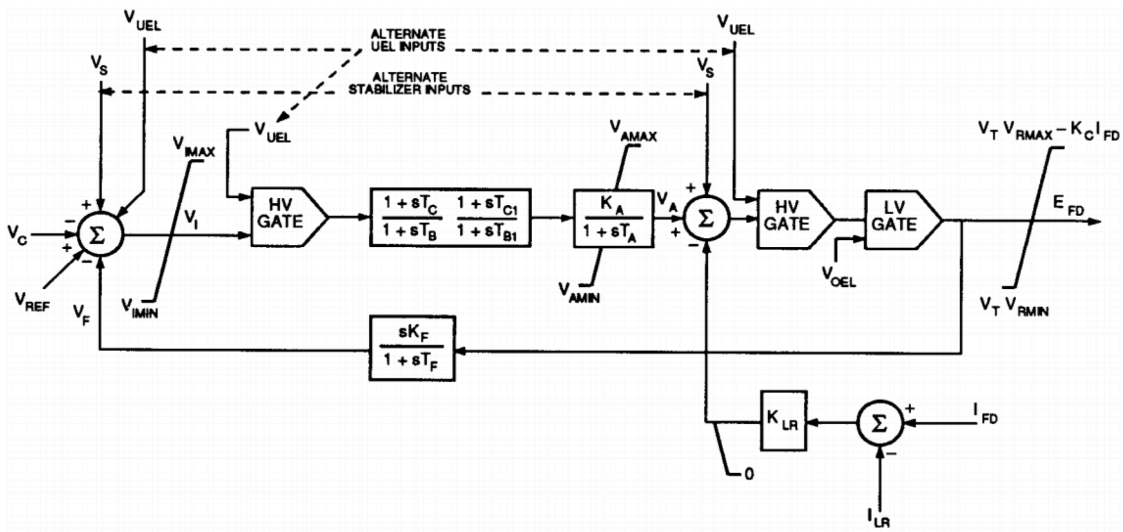

Fig 2.9 Structure of exciter system

In this type of system, the inherent exciter time constants are very small, and exciter stabilization may not be required. On the other hand, it may be desirable to reduce the transient gain of these systems for other reasons. The model shown is sufficiently versatile to represent transient gain reduction implemented either in the forward path via time constants, T_B and T_C (in which case K_F would normally be set to zero), or in the feedback path by suitable choice of rate feedback parameters, K_F and T_F. Voltage regulator gain and any inherent excitation system time constant are represented by K_A and T_A, respectively. The time constants, T_{C1} and T_{B1}, allow for the possibility of representing transient gain increase, with T_{C1} normally being greater than T_{B1}.

The hydro generator adopts two control strategies: PQ and Droop control

This chapter sets up the strategy to make most use of renewable energy. When ‘wind + battery + hydro’ microgrid connected with utility grid, the frequency is supported by utility grid. The battery reserve is only used to adjust active power and restrain the voltage change caused by active power change from wind turbine. When operating under island mode, hydro generation will be the main control unit to keep voltage and frequency stable. This chapter also illustrates the control strategies of wind turbine, battery reserve and hydro generation and structure of each unit.

CHAPTER III

MODELING AND CONTROL ANALYSIS OF MICROGRID

3.1 The operation of microgrid

This chapter will state a typical microgrid in an area with sufficient wind and hydro energy.

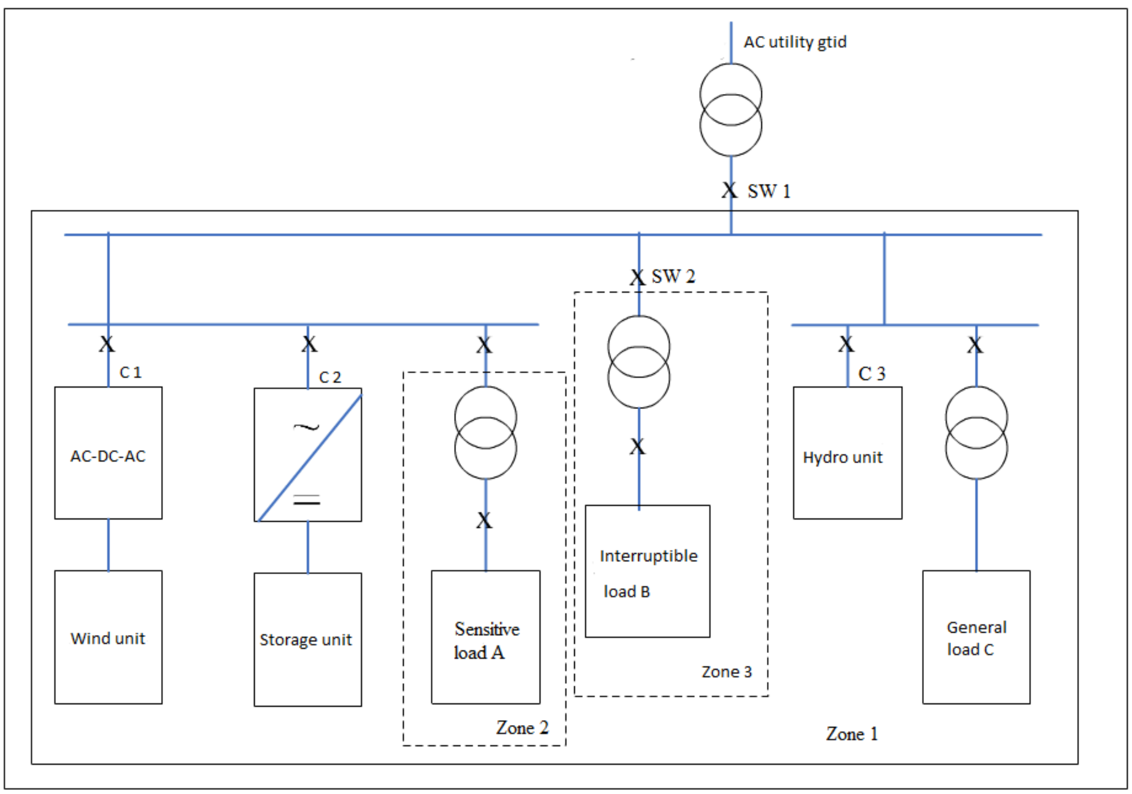

Fig 3.1 A typical structure of microgrid

In the Fig 3.1, wind turbine unit transfers wind energy to electric power by direct-driven synchronous generator. The electric power from direct-driven synchronous generator is transmitted to AC bus. The electric power on the AC bus can be used to charge the battery or support local loads. It is also possible to provide the extra power to utility grid when the demand within microgrid is less than the power generated.

Under the grid-connected mode, all the loads will be supported by utility grid of ‘wind + battery + hydro’ microsources. No matter the microsources are working or not, it doesn’t affect the system operation stability. But in the island operation mode, wind turbine, battery, and hydro support the power to microgrid together. Hydro is main control unit to keep voltage and frequency stable. Wind turbine is working at its maximum capacity. The battery reserve works as backup to compensate the fluctuation of wind turbine output. If the load demand is less than the power generated, the microgrid will keep the wind output but reduce the hydro output. To increase reliability, in both grid-connected mode and island mode, the microgrid needs power management to control the microsource power output.

The wind energy and battery output are limited by capacity. In island mode, the microgrid may be not able to support all loads. The microgird needs load management when operation in island mode.

Load management and power management are to keep output and loads balance at any time. Power management also takes part in microsources load distribution and controlling microsources to provide continuous power. On the other hand, load management assists power management to restrain the power quality in the microgrid.

3.1.1 Power management

Storage unit will be backup power to compensate the fluctuation of wind turbine output to increase power quality. Hydro unit will be the main control unit to provide steady state power and transient power under island operation mode and keep voltage and frequency. In the grid-connected mode, wind turbine will operate as maximum power output curve. The storage will compensate the fluctuation of wind turbine output.

Steady state power management

Both in grid-connected and island modes, steady state power management takes part in transferring the microsource power in ‘wind + hydro+ storage’ system.

The strategies listed below will be adopted under grid-connected mode:

1) Wind turbine unit operates at maximum power output mode, hydro unit is controlled by PQ control, and battery is in charging mode.
2) When storage is full, the battery will be in float charging.
3) When running out of wind and hydro energy, utility grid alone is charging the storage.

The strategies listed below will be adopted under island mode:

1) Wind energy is not able to provide enough energy to loads, ‘wind + hydro+ storage’ will support the load together.
2) Wind and hydro output is larger than loads, reduces the hydro energy.
3) Wind output is larger than loads, charges the battery.
4) Battery supports the load alone when wind and hydro disappear.
5) When battery is full, but wind output is larger than loads, uses variable pitch angle control to reduce wind output.

Transient power management

The focus of transient power management is the transient power imbalance in operation process. Under the grid-connected mode, the change caused by wind speed and loads will response on the power transferred on grid bus. In the other word, in ‘wind + hydro + storage’ grid-connected mode, the utility grid is providing transient power support. Under island mode, the storage unit is absorbing the transient power of wind energy. The hydro energy is used to fulfill steady state power. When wind and hydro disappear, storage unit alone will provide both steady state power and transient power.

3.1.2 Load management

In this thesis, a simple interruptible load is connected into the microgird by switch SW2. Under island mode operation, to keep the reliable supplement to sensitive load A, the interruptible load B is cut off. Unless the whole microgrid breaks down, the sensitive load A is always connected into the microgrid. Near the hydro generator, the general load C will be connected or cut off according to the state of hydro generator.

3.2 State transition

According to Fig 3.1 structure of microgrid, ‘wind + hydro + storage’ system has two operation modes: grid-connected mode and island mode.

Under each mode, there are two possible operation states: steady state and transient state. Under steady state, load and generation are in balance. However, under transient state, there is transient different between load and generation. To keep stable, the system will be steady at next balance point. The transient state can divided into planed transient and accidental transient.

Planned transient means the outcome of planned controlling switches, such as cutting off the bus when repairing. Accidental transient is the result of random fault of system. Both planned and accidental transient will change the combinations of microsources in the microgrid. The change of microsources combination will lead to operation state transition.

There are several possible operation states in ‘wind + hydro + storage’ system. It is a very difficult problem for control system to control ‘wind + hydro + storage’ system and evaluate stability without analysis tools. By reducing the number of states, the control strategy will manage the microgrid more efficiently. The Fig 3.2 gives out the system sources combination transition diagram.

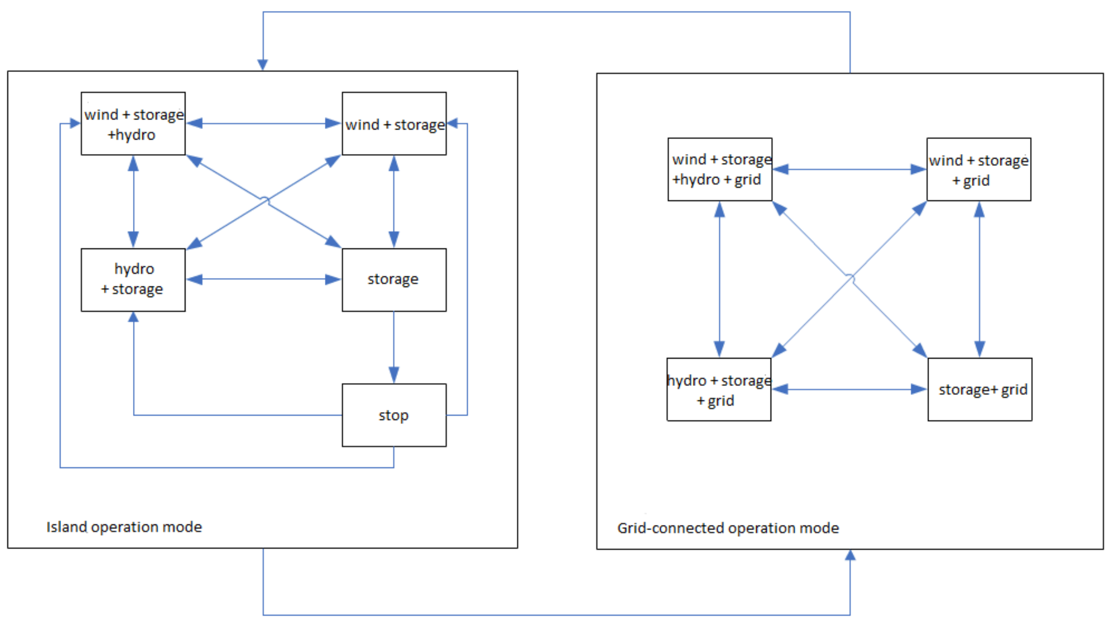

Fig 3.2 ‘wind + hydro + storage’ system sources combination transition diagram

Because of high intermittence of wind power and hydro energy’s slow response to fast change, no matter grid-connected or island mode, to reduce the fluctuation in system, generally, storage unit is adopted in each state. Under grid-connected mode, when wind energy is sufficient for all loads, the microgrid system is in ‘wind + storage + hydro + utility grid’ condition; when wind energy is gone, the microgrid is in ‘hydro + storage + utility grid’ condition; when both wind and hydro are gone, the microgrid is in ‘storage + utility grid’ condition.

In the island operation mode, distinguished by microsources combinations, there are 5 steady states"

1.) 'stop', microsources stop giving out power
2.) 'storage', only storage unit supports the load
3.) 'wind + storage', wind and storage units are providing power
4.) 'hydro + storage', hydro and storage units are providing power
5.) 'wind + storage + hydro', 3 microsources together are operating to support the load

3.3 Control strategy and design

The controller will manage the 'normal operation' states listed as below:

Grid-connected mode

1) storage – utility grid
2) wind – storage – utility grid
3) hydro – storage – utility grid
4) wind – storage – hydro – utility grid

Island mode

1) storage
2) wind – storage
3) hydro – storage
4) wind – storage – hydro

'Normal operation' includes steady state, and also transient state caused by load or switch. In every operation state, there is different control strategies to manage the 'wind + storage + hydro' system. Every control strategy will fulfill the demand under each specific operation state. And the control strategy will change according to the operation state change.

Fig 3.1 illustrates a typical microgrid structure in an area with sufficient wind and hydro energy. This structure contains sensitive load and interruptible load. Generally, the power system is connected with utility grid to support loads or transfer power to utility grid. If fault occurs in the utility grid, wind and hydro will support the loads together. After wind and hydro running out, the storage will be able to support sensitive load for a short time.

Power from hydro is AC power, which can directly inject into the utility grid. But for the wind energy, it needs to go through rectifiers and inverters. Then the wind energy is able to inject into the grid. Battery storage is DC power. To connect the grid, battery power needs to go through a DC/AC converter. Compared with DC power system, AC power system is more reliable and flexible.

Zone 1 in Fig 3.1 is AC microgrid. Zone 2 is the sensitive AC load A near local storage unit. Zone 3 is the interruptible load B connected to AC bus. Load C near hydro generator is uncontrolled load. It will follow the hydro generator to join or quit the microgrid.

There are 4 independent power sources: utility grid, storage (emergency power), wind power (main power), and hydro power (main power). Whether the power source is in use or not, there is 16 different operation states. For each state, the sensitive load in Zone 2 is working continuously. Taking the interruptible load in Zone 3, controlled by switch 2 (SW2), into consideration, connected or not, the number of operation states is multiplied by 2, which is 32. The Table 1 expresses all the possible operation states. '1' represents power source is working; '0' represents power source is not working. '1' indicates load is connected; '0' indicates load is cut off.

Number	Utility grid	Wind	Storage	Hydro	Load B	Operation state
1	0	0	0	0	0	Stop (1)
2	0	0	0	0	1	Stop
3	0	0	0	1	0	
4	0	0	0	1	1	Hydro (2)
5	0	0	1	0	0	Emergency(3)
6	0	0	1	0	1	
7	0	0	1	1	0	
8	0	0	1	1	1	Hydro
9	0	1	0	0	0	
10	0	1	0	0	1	
11	0	1	0	1	0	
12	0	1	0	1	1	Self support (4)
13	0	1	1	0	0	Emergency
14	0	1	1	0	1	
15	0	1	1	1	0	
16	0	1	1	1	1	Self support
17	1	0	0	0	0	
18	1	0	0	0	1	Input (5)
19	1	0	0	1	0	
20	1	0	0	1	1	Hydro output (6)
21	1	0	1	0	0	
22	1	0	1	0	1	Input
23	1	0	1	1	0	

24	1	0	1	1	1	Hydro output
25	1	1	0	0	0	
26	1	1	0	0	1	Wind output (7)
27	1	1	0	1	0	
28	1	1	0	1	1	Utility grid support (8)
29	1	1	1	0	0	
30	1	1	1	0	1	Wind output
31	1	1	1	1	0	
32	1	1	1	1	1	Utility grid support

Table 1 All the possible operation states

In island operation mode, storage unit is compensating the fluctuation of wind energy output and responding to fast load change. In the grid-connected mode, storage unit is charging, preparing to switch to island mode. Thus, in every operation state, storage unit must be considered as connected to the microgrid. That means state 4 and 8, 5 and 13, 12 and 16, 18 and 22, 20 and 24, 26 and 30, 28 and 32 are the same state. State 17, 19, 21, 23, 25,27, 29,31 are not practical states. They mean the utility grid is working, but the load is disconnected by SW2, which is impossible. Wind energy cannot support sensitive load alone. So, state 9 and 10 are eliminated. Assuming that the hydro would cover all the demand, in microgrid 'wind + hydro' and 'hydro' modes, the state 3, 7, 11, 15, which do not include load in Zone 3, are out of consideration. Under the 'storage' and 'storage + wind' modes, to keep sensitive load A operating normally, load B is cut off. States 6 and 14 are removed. At last, there are only 8 states listed in the last column. Fig 3.3 shows the 8 remaining states and their relationships.

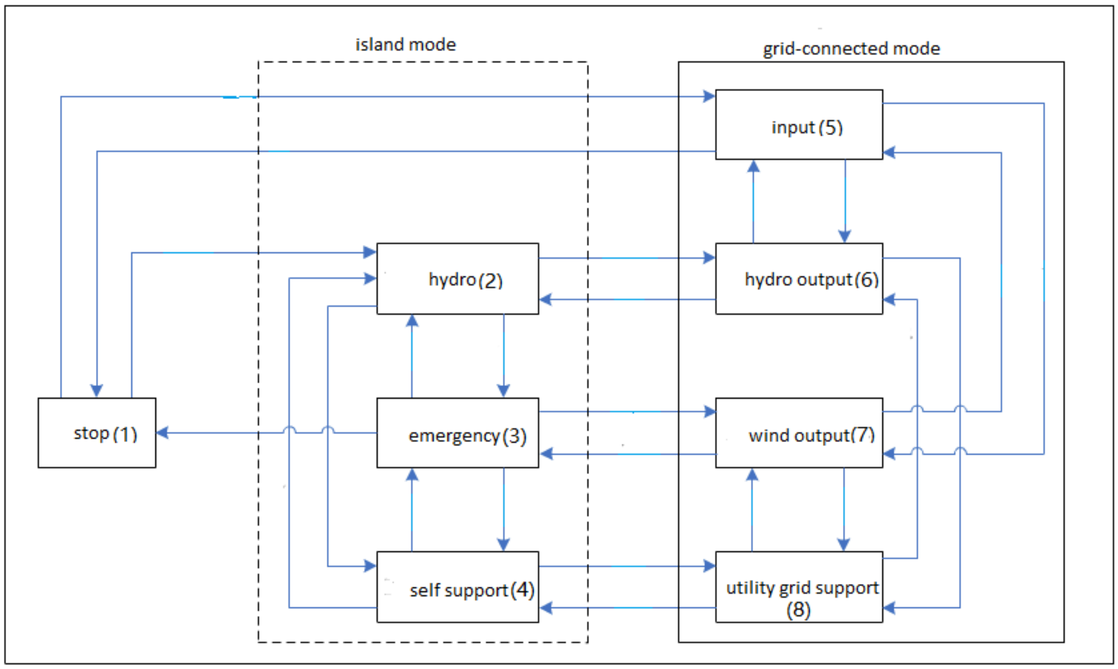

Fig 3.3 8 remaining states and their relationships.

Under 'Hydro' state, the hydropower output is covering all the load demand in whole microgrid. The interruptible load B is also connected in the microgrid. When utility grid is in fault, the operation state in island microgrid is 'self support 'state, which includes wind, hydro, storage and all loads. Under 'self support' state, the microgrid makes maximum use of wind energy and insures the support to sensitive load A. Under 'Emergency' state, the battery and wind energy only support sensitive load A. At this time, battery, wind turbine and load A are the only components in the microgrid.

In grid-connected mode, the main operation state is 'utility grid support'. Wind turbine is controlled by maximum power point tracking method to support loads. Battery is charging. Hydro generator gives out specific active and reactive power.

According to the statement above, there are 8 different operation states in AC microgrid. Every transition is a result of one event. Table 2 lists the accidental events that lead to state transition.

Letter	Events
A	Grid fault
B	Grid recovery
C	Wind unit fault
D	Wind unit recovery
E	Hydro fault
F	Hydro recovery
G	Storage exhausted

Table 2 Events lead to state transition

Combine Table 1 and Table 2, system state transition diagram (Table 3) and system mode transition diagram (Table 4) are listed below:

Table 3 System state transition diagram

Operation mode	State transition	Description	Events
Island mode	(1)-(2)	Stop - hydro	Hydro recovery (F)
	(1)-(3)	Stop - emergency	
	(1)-(4)	Stop – self support	
	(2)-(1)	Hydro - stop	
	(2)-(3)	Hydro- emergency	Hydro fault (E)
	(2)-(4)	Hydro- self support	Wind unit recovery (D)
	(3)-(1)	Emergency- stop	Storage exhausted (G)
	(3)-(2)	Emergency-hydro	Hydro recovery (F) without wind energy
	(3)-(4)	Emergency-self support	Hydro recovery (F) with wind energy
	(4)-(1)	Self support- stop	
	(4)-(2)	Self support- hydro	Wind unit fault (C)
	(4)-(3)	Self support- emergency	Hydro fault (E)
Grid-connected mode	(5)-(6)	Input-hydro output	Hydro recovery (F)
	(5)-(7)	Input-wind output	Wind unit recovery (D)
	(5)-(8)	Input-utility grid support	
	(6)-(5)	Hydro output-input	Hydro fault (E)
	(6)-(7)	Hydro output-wind output	
	(6)-(8)	Hydro output-utility grid support	Wind unit recovery (D)
	(7)-(5)	Wind output- input	Wind unit fault (C)
	(7)-(6)	Wind output-hydro	

		output	
	(7)-(8)	Wind output- utility grid support	Hydro recovery (F)
	(8)-(5)	Utility grid support - input	
	(8)-(6)	Utility grid support – hydro output	Wind unit fault (C)
	(8)-(7)	Utility grid support- wind output	Hydro fault (E)

Table 4 Operation mode transition diagram

Mode transition	State transition	Description	Event
Grid-connected mode- island mode	(5)-(1)	Input-stop	Grid fault (A)
	(6)-(2)	Hydro output- hydro	Grid fault (A)
	(7)-(3)	Wind output- emergency	Grid fault (A)
	(8)-(4)	Utility grid support – self support	Grid fault (A)
Island mode- grid-connected mode	(1)-(5)	Stop-input	Grid recovery (B)
	(2)-(6)	Hydro-hydro output	Grid recovery (B)
	(3)-(7)	Emergency- wind output	Grid recovery (B)
	(4)-(8)	Self support- utility grid support	Grid recovery (B)

According to Table 3 and Table 4, Fig 3.4 is the microgrid state transition structure.

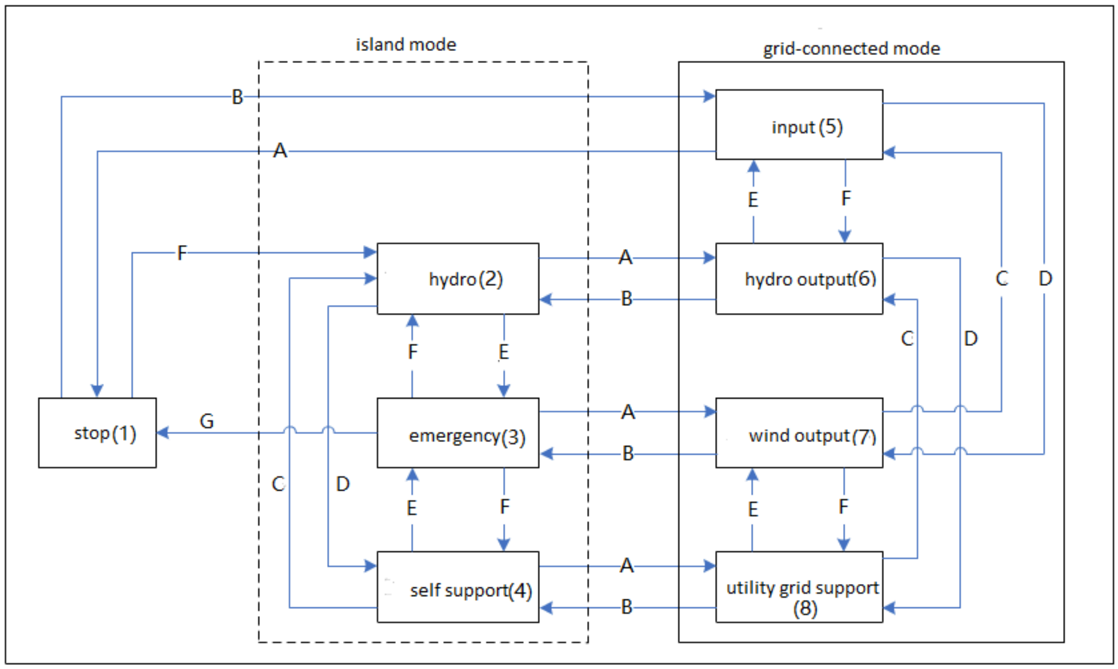

Fig 3.4 Microgrid state transition structure

Control system design

There are many controlled components in this typical microgrid. As shown in Fig 3.1, they are wind unit C1, storage unit C2, hydro unit C3, switch SW1 and SW2. A control system will coordinate all the components. To make most use of renewable energy, wind turbine is always giving out maximum power output. The wind unit C1 is controlled by PQ control to ensure the maximum active power output. When connected to the utility grid, storage unit is in float charging. In island mode, storage unit will be under V/F Droop control to keep AC bus voltage stable. SW1 is used to connect or disconnect to utility grid. When SW2 is open, Zone 3 will be cut off from the microgrid so that the sensitive load in Zone 2 will operate generally. Table 5 illustrates the operation state of each component. ‘0’ is not operating, ‘1’ is operating.

Number	Operation state	C1	C2	C3	SW1	SW2
1	Stop	0	0	0	0	0
2	Hydro	0	PQ	Droop	0	1
3	Emergency	PQ	Droop	0	0	0
4	Self support	PQ	PQ	Droop	0	1
5	Input	0	Charge	0	1	1
6	Hydro output	0	Charge	PQ	1	1
7	Wind output	PQ	Charge	0	1	1
8	Utility grid support	PQ	Charge	PQ	1	1

Table 5 Operation state of each component

If any component changes, the control system will change the operation state to another to keep the microgrid balance and stable.

The main statements of this chapter states are:

1. A typical microgrid structure in an area with sufficient wind and hydro.
2. Introduction to power and load management under grid-connected and island mode.
3. Illustration of each state, and design of the transition diagram.
4. Control strategies for each component.

CHAPTER IV

SIMULATION AND ANALYSIS OF MICROGRID OPERATION STATES

This chapter will simulate the 'wind + storage + hydro' mix power microgrid model., and analyze the state transition. The state transition includes that self support (4)- emergency (3), self support (4)- utility grid support (8) and emergency (3)- wind output (7). By simulating the transient characteristics, the results of voltage and frequency on sensitive load A are given.

4.1 Simulation model

The simulation structure of 'wind + storage + hydro' mix power microgrid is shown as Fig 4.1. There is a 1MW direct-driven variable speed wind turbine generator connected the microgrid with inverters and transformer. For the battery, the voltage is DC 2.8 kV connected the microgrid with inverters. 10 hours rated power output is 1.96 MW. The capacity of hydropower station is 5MW. Going through a transformer, the hydro generator connects with the microgrid. The microgrid is connected to a 20 MVA utility grid with 10 kV voltage by a 3.05 km line. The lines in this model are 10 kV voltage. The unit impedance is $Z_1 = 0.21 + j0.35\ \Omega/km$, $Z_0 = 0.48 + j0.97\Omega/km$. Loads are constant power load. The detail parameter of wind and hydro generator is in appendices.

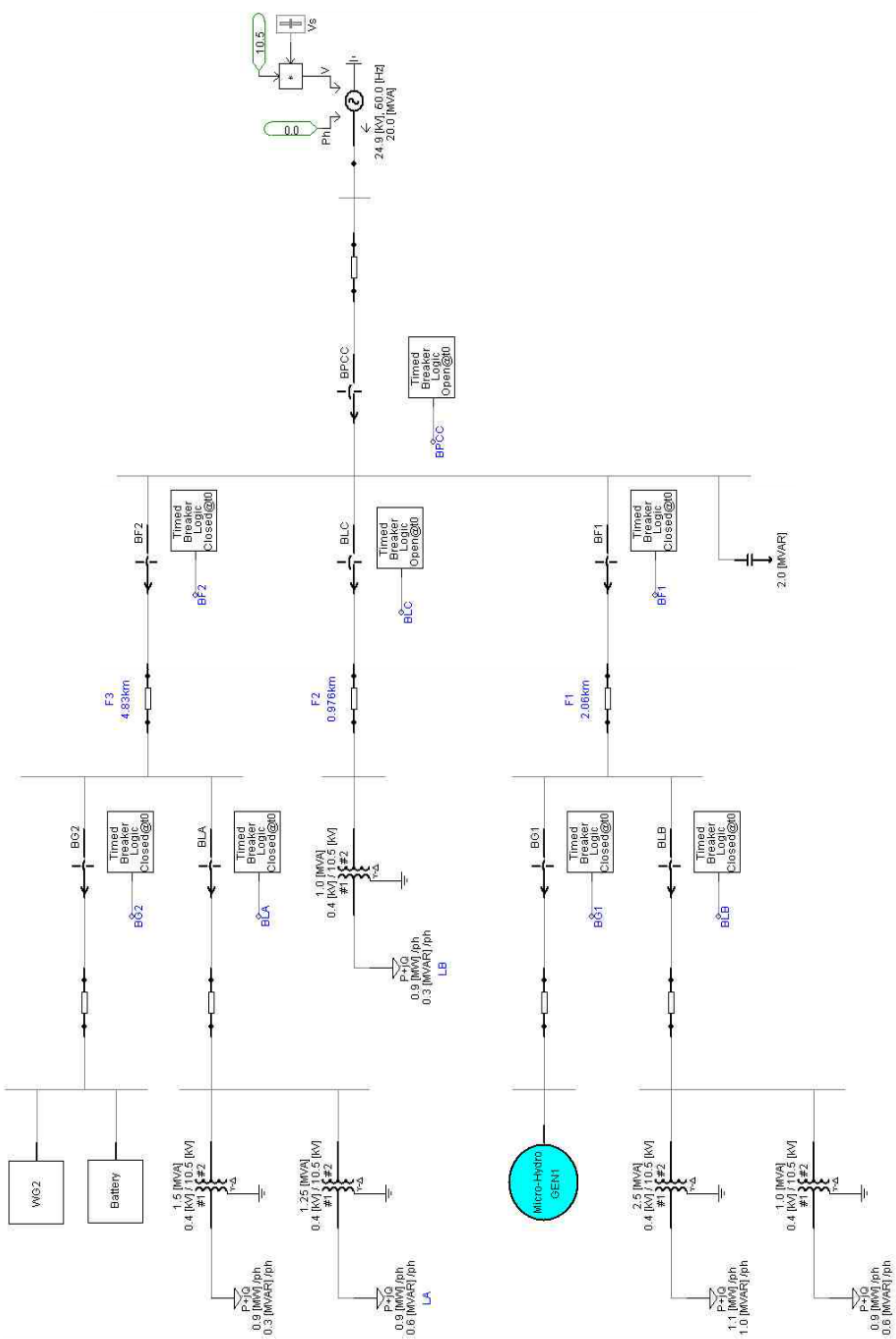

Fig 4.1 The simulation structure of ‘wind + storage + hydro’ mix power microgrid

4.2 States of normal operation

To make most use of wind energy and ensure the reliability on sensitive load, when under grid-connect mode, the microgrid is operation under utility grid support state (wind + storage + hydro + utility grid). When under island mode, microgrid is operating under self support state (wind + storage + hydro). These two states are the main normal operation states.

4.2.1 Utility grid support state

In this state, fluctuation of wind generation is supported by utility grid. The voltage and frequency are also supported by utility grid. Battery is charging. Generally, to charge the battery to full, it may takes 2 hours. To reduce the charging time to 2 hours, increasing charging current is an option. When battery is almost full, the charging strategy changes to float charging. In the simulation, the model considers the charging battery as a load.

The Fig 4.2 is wind speed. Fig 4.3 is active power and reactive power curve of wind turbine. Active power changes according to the wind speed and reactive power is almost zero.

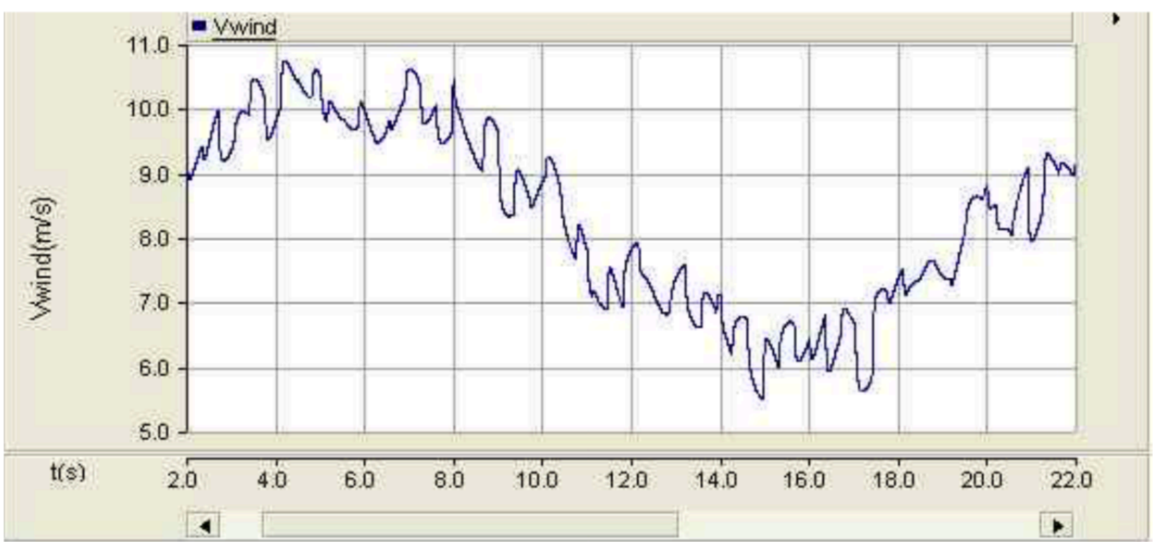

Fig 4.2 Wind speed

Fig 4.3 is active power and reactive power given out by wind turbine.

Fig 4.3 Active power and reactive power

Fig 4.4 is wind power coefficient.

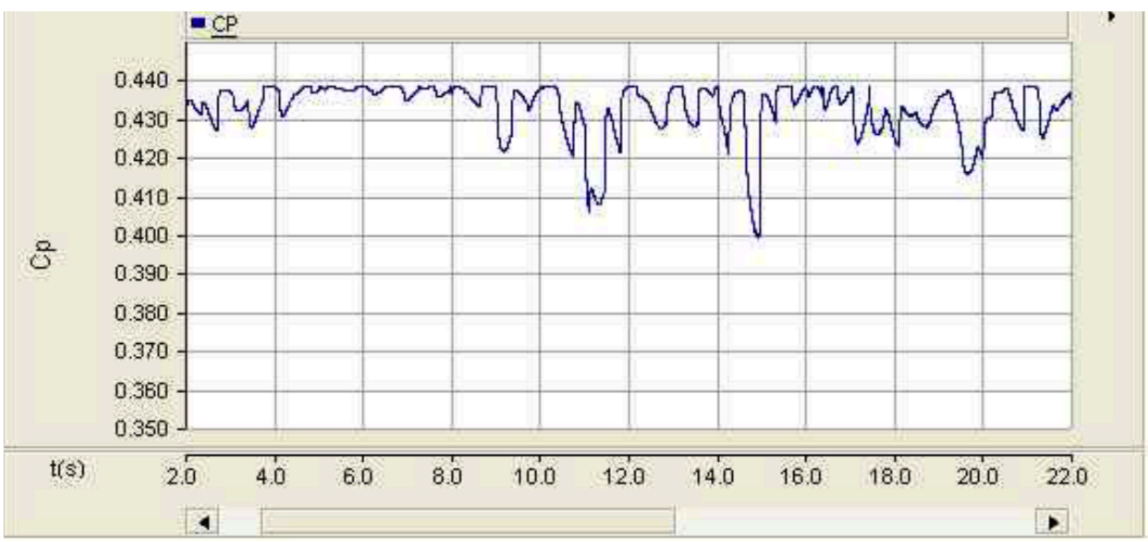

Fig 4.4 Wind power coefficient

Due to the wind speed change, the wind power coefficient keeps around 0.435.

Fig 4.5 is rotating speed of wind turbine.

Fig 4.5 Rotating speed of wind turbine

When wind speed is larger than the rated wind speed, the pitch angle control comes into use. Fig 4.6 is the system wind speed when actual wind speed is larger than rated wind speed.

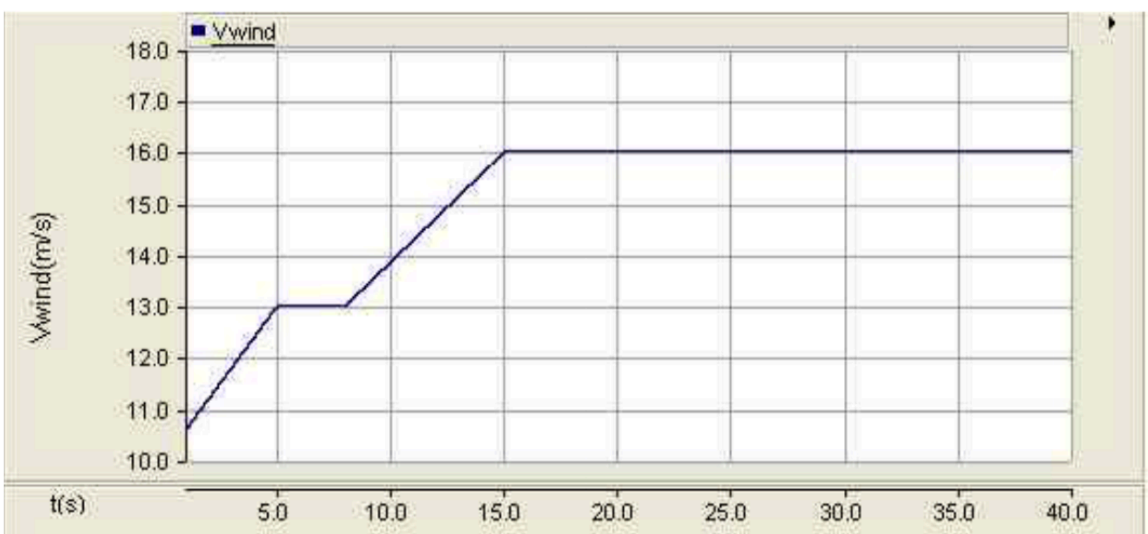

Fig 4.6 System wind speed when actual wind speed is larger than rated wind speed

Fig 4.7 shows the rotating speed of wind turbine according to the Fig 4.6

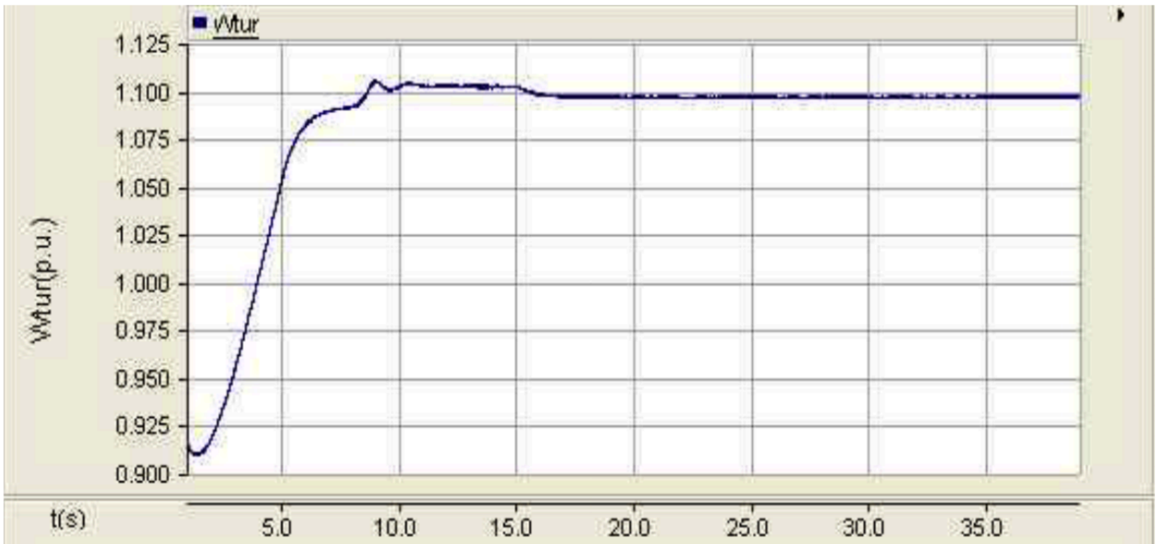

Fig 4.7 Rotating speed of wind turbine according to the Fig 4.6

Fig 4.8 indicates the pitch angle when actual wind speed is larger than rated wind speed.

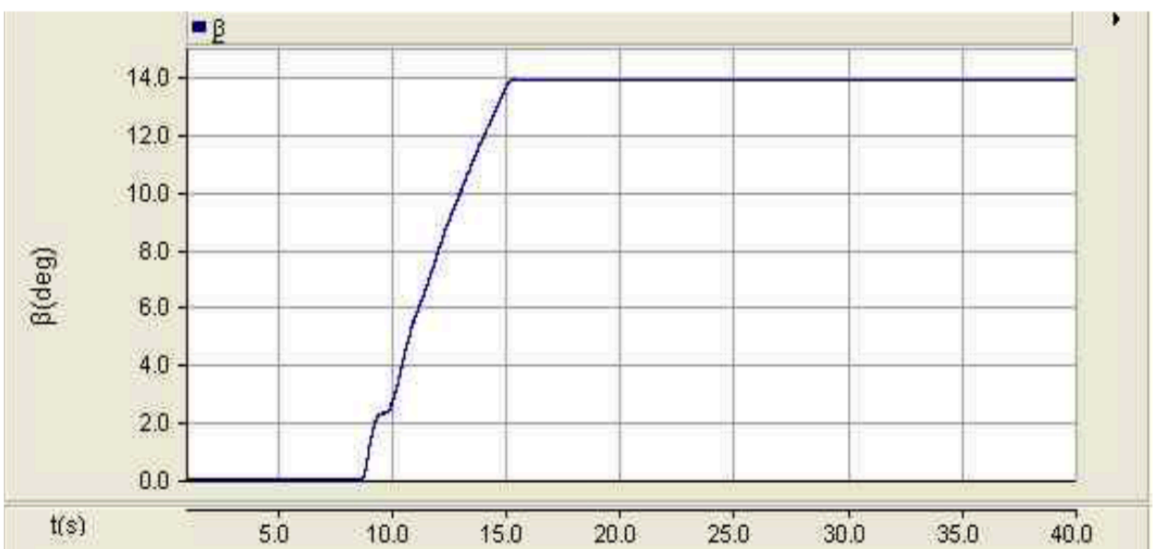

Fig 4.8 The pitch angle when actual wind speed is larger than rated wind speed

When wind speed is 1.1 rated speed, the variable pitch control is in use to keep wind turbine rotating speed at 1.1 rated rotating speed and stable pitch angle at a certain degree.

In utility grid support mode, the power fluctuation caused by wind is supported by utility grid. The hydropower station is operating at rated state. Fig 4.9 shows the voltage value at load. Fig 4.10 shows the power frequency at load. The value keeps at 1.0 p.u. And frequency keeps at 60Hz. It fulfills the load power demand.

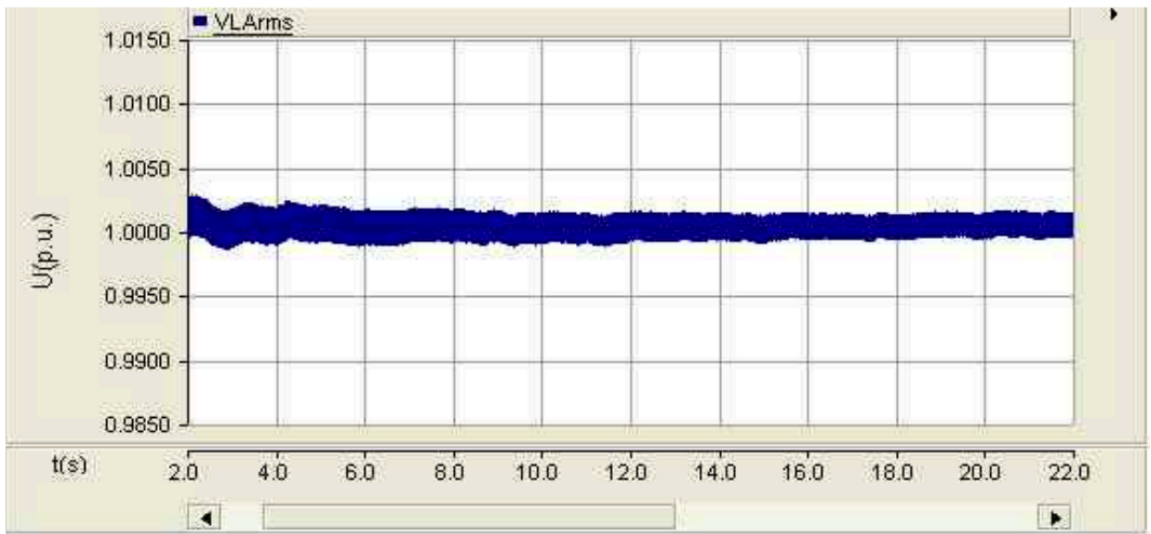

Fig 4.9 Voltage value at load

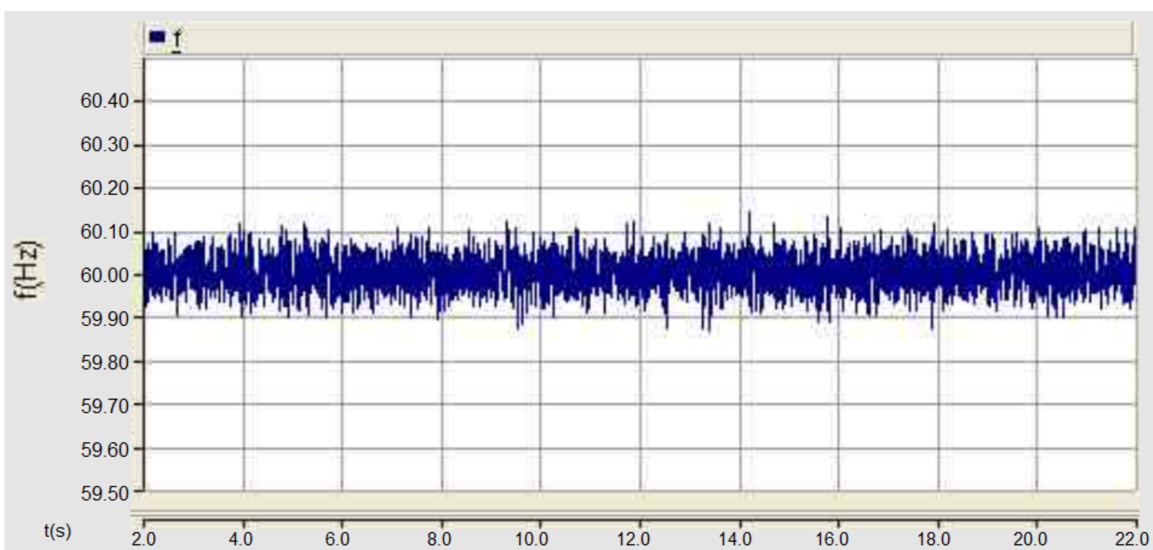

Fig 4.10 Voltage frequency at load

Fig 4.11 shows the active power and reactive power of hydropower station. Active power keeps at 5MW, and reactive power almost keeps at 0.

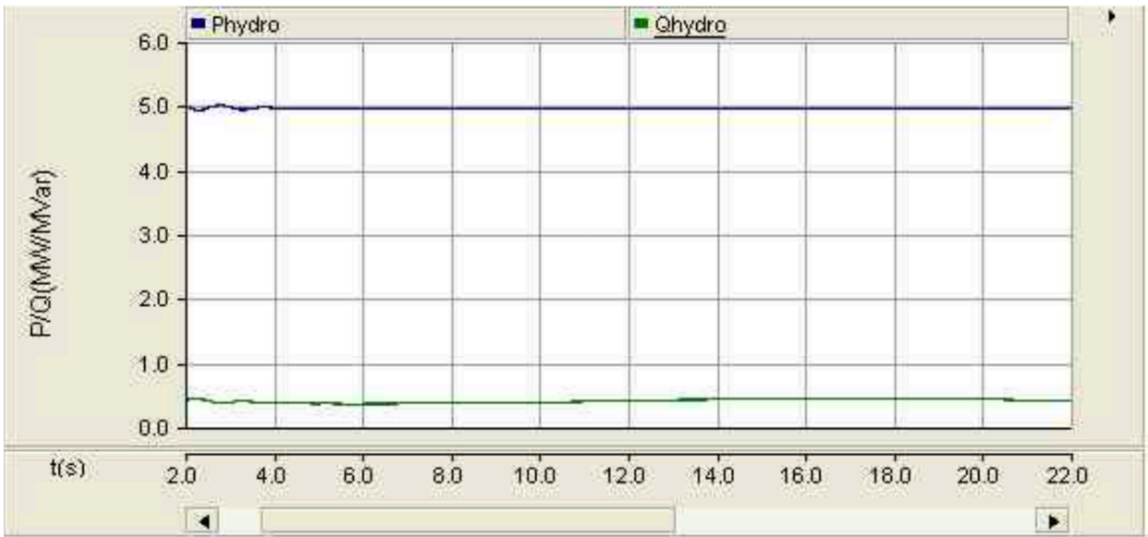

Fig 4.11 The active power and reactive power of hydropower station

4.2.2 Self support state

In this state, microgrid is operating under island mode. Hydropower station is the main power output. Battery compensates the wind power fluctuation. Battery uses PQ control to keep battery and wind power output constant. In this state, wind speed is shown as Fig 4.2. The active power and reactive power output of wind energy are the same as Fig 4.3. Fig 4.12 and Fig 4.13 shows the 'wind +battery' and 'battery' active and reactive power.

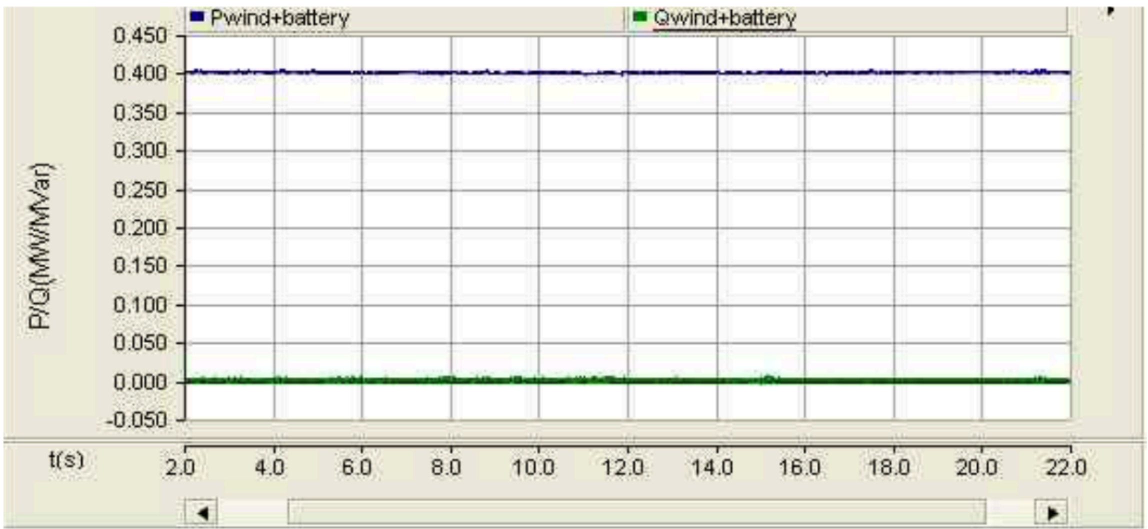

Fig 4.12 ‘wind + battery’ active and reactive power

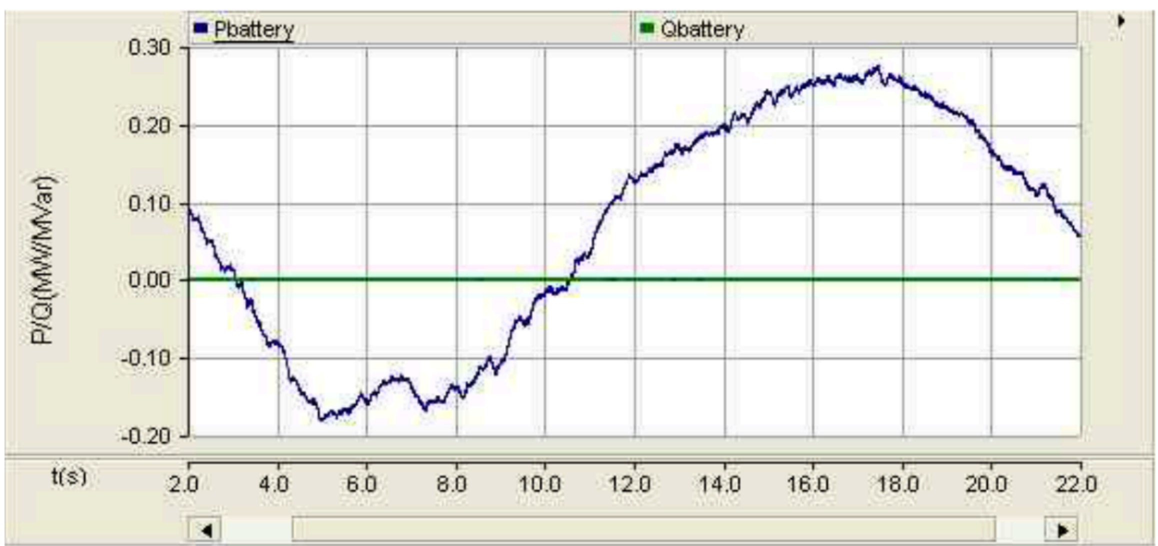

Fig 4.13 ‘battery’ active and reactive power

Fig 4.14 shows the voltage fluctuation at load A with battery and without battery. As Fig 4.14 shows with battery compensating the fluctuation of wind power, the voltage keeps at constant value. Fig 4.15 shows the frequency comparison. With battery, the frequency keeps as constant.

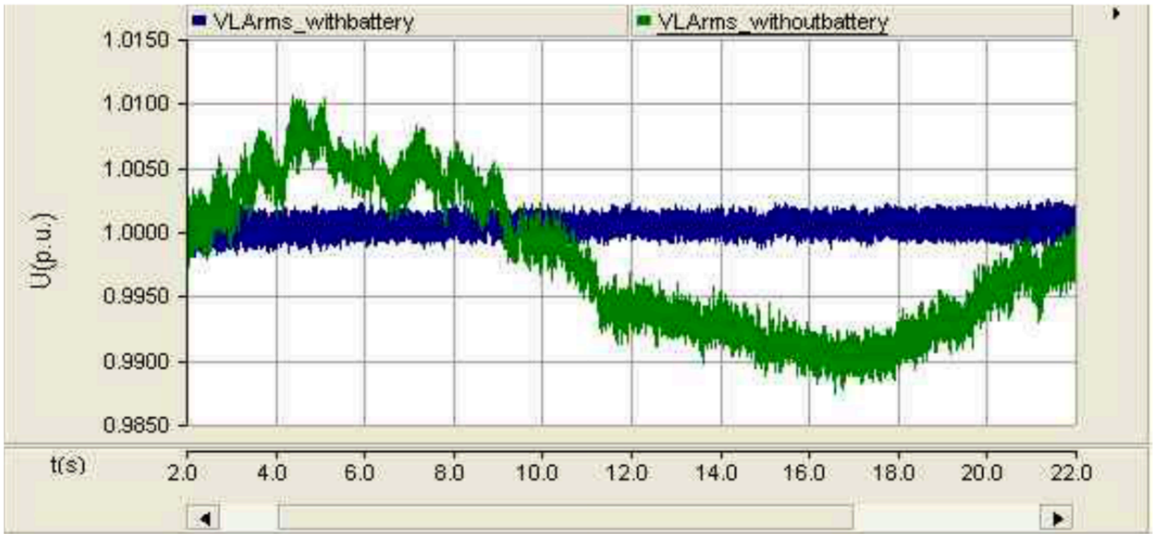

Fig 4.14 Voltage comparison with and without battery compensation

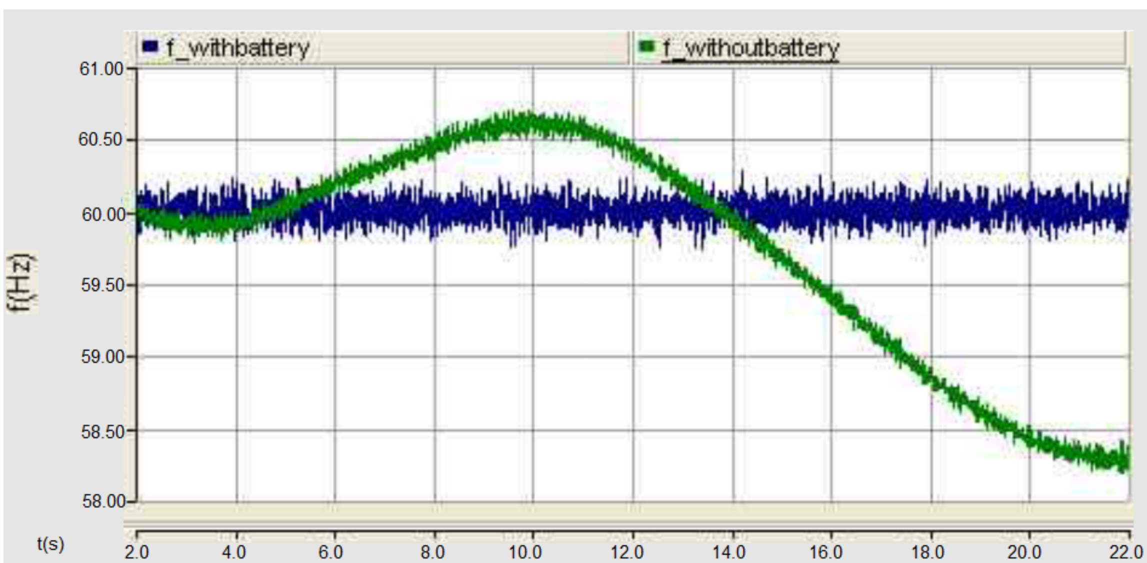

Fig 4.15 Frequency comparison with battery and without battery

4.3 From self support state to emergency state

In island mode, when hydropower station fault occurs, the microgrid will transfer from self support state to emergency state. Under emergency state, batterymust be used to compensate the power fluctuation caused by wind turbine. Taken the high cost and limited lifetime of battery into consideration, the battery storage is only supporting sensitive load A. In this case, the battery will use V/F Droop control to keep voltage and frequency. At the same time, interruptible load B is cut off.

In emergency state, if the battery runs out, the island mode microgrid will stop operating. Set sensitive load A 2.1+j0.9MVA, interruptible load B 0.9+j0.3MVA. Assume the hydropower station is cut off ate 0.5s. To meet the load active and reactive demand, battery needs to increase active power and reactive power. At 0.52s, interruptible load B is cut off. At this time, the battery still needs to increase active power, but the reactive power is more than demand. According to P/f and Q/V Droop control, the battery changes the active and reactive power to keep balance. Fig 4.16 shows the active and reactive power curves. The Fig 4.17 shows the frequency on the load A. Fig 4.18 shows the voltage on the load A.

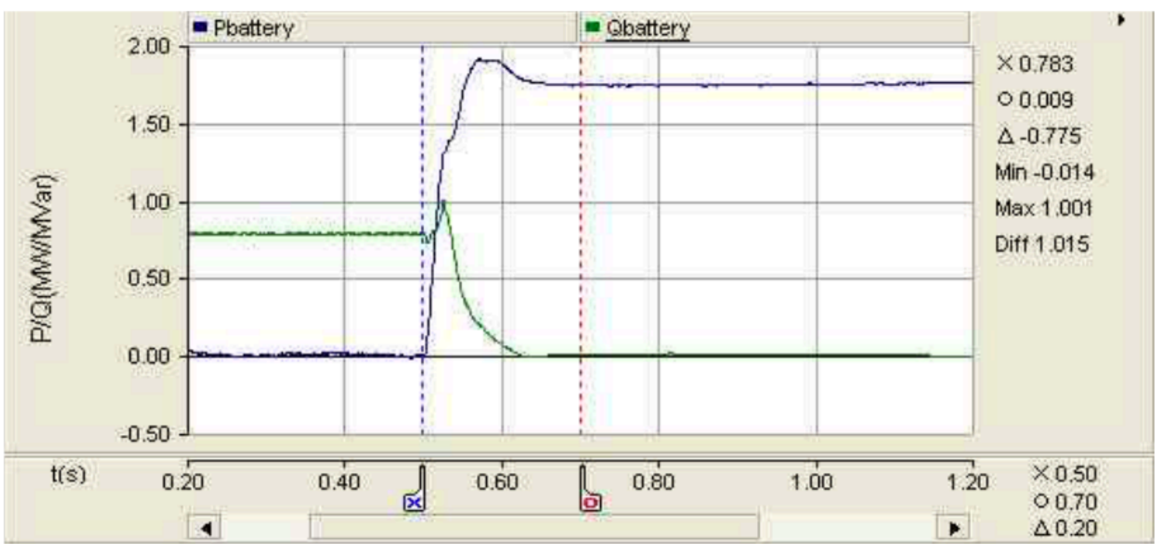

Fig 4.16 Battery active and reactive power

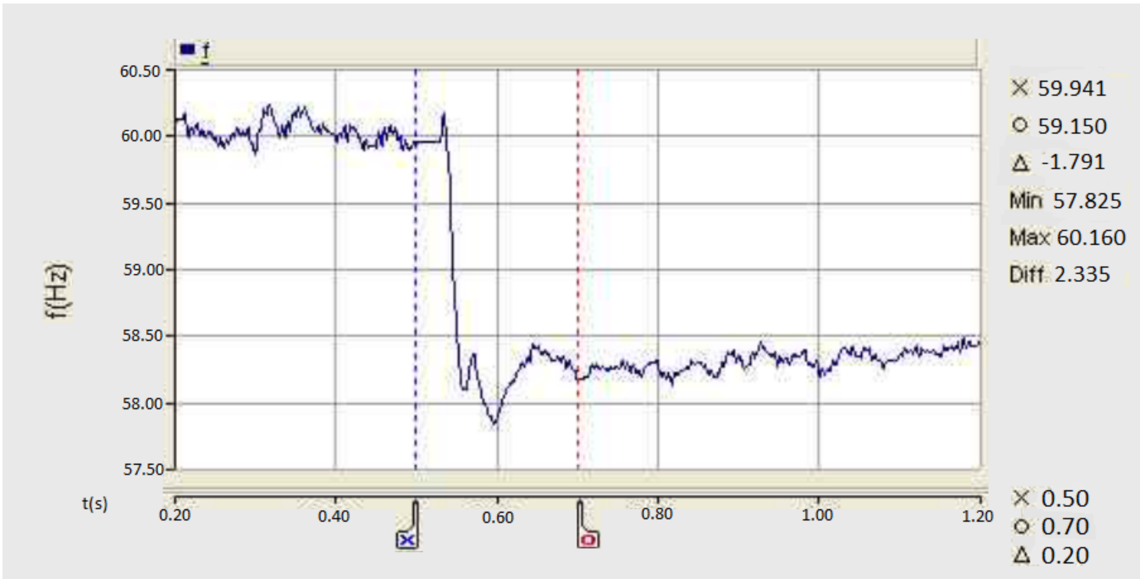

Fig 4.17 Voltage frequency on sensitive load A

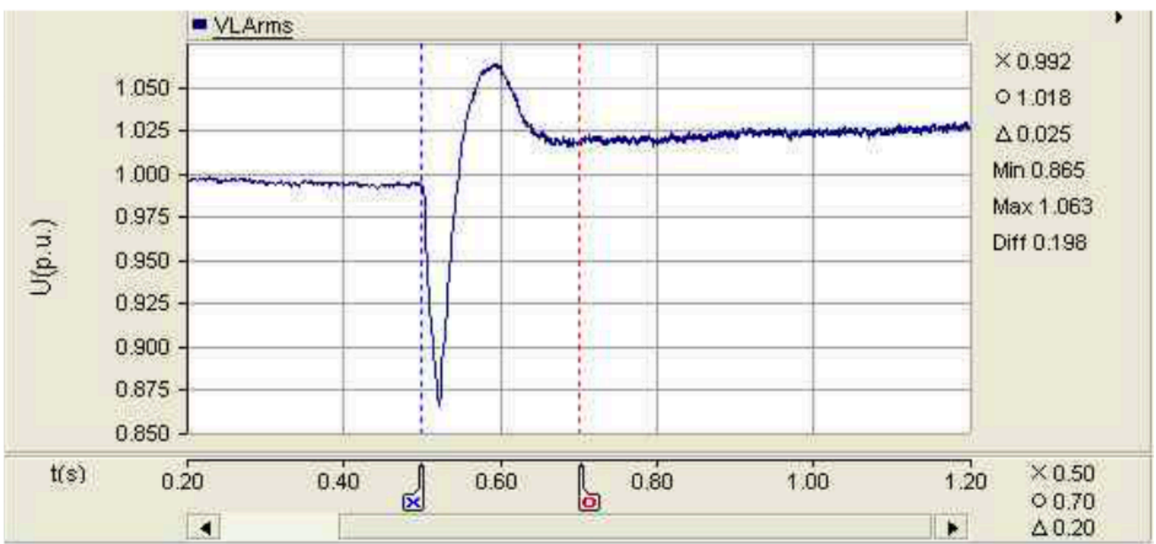

Fig 4.18 Sensitive load A voltage

The Droop control of battery makes the frequency drops 2 Hz. It is related to droop coefficient. In this simulation, the model sets droop coefficient as 0.7507MW/Hz.

4.4 From self support state to utility support state

The main factors of microgrid changing grid-connected mode to island mode are utility grid fault and fault inside microgrid. The former factor will transfer microgrid from grid-connected mode to island mode. In island mode, microgrid will ensure the reliability on local loads to avoid the blackout due to utility grid fault. The latter factor will cut the microgrid off from the utility grid to avoid the fault in a local area spread to a large area and reduce the effect of connecting to utility grid. One important problem for microgrid is how to reconnect to utility grid. The microgrid needs sensor the voltage and current at point of common coupling (PCC) to reconnect to utility grid. When utility grid is operating normally, it is time to reconnect the microgrid. Fig 4.19 shows the instantaneous voltage at PCC.

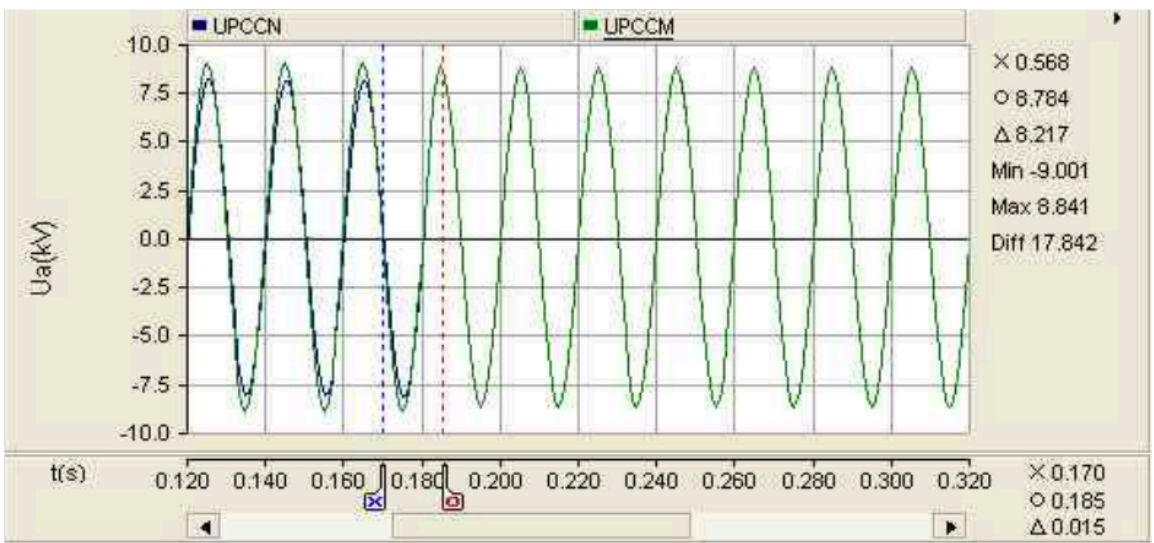

Fig 4.19 Instantaneous voltage curves on PCC switch

Because of hydropower station, the frequency in island mode keeps at 60 Hz. When reconnecting to utility grid, microgrid control system only needs to keep the voltage phase same as utility grid voltage.

4.5 From emergency state to wind output state

Emergency state is able to operate in a short time. To keep supporting sensitive load A, once utility grid is recovered, microgrid needs to reconnect to utility grid immediately. In emergency state, the frequency is a little lower than 60 Hz. There will be a large transient state process. Considering the high cost and limited lifetime, battery is only discharging when active power is not sufficient under island mode. In other situations, battery is used to compensate the fluctuation of wind power. Fig 4.20 shows the instantaneous voltage on PCC switch. Because of different frequency, the two voltage lines superpose at time t=1.627s. Fig 4.21 shows the instantaneous current curve of direct-driven wind generator.

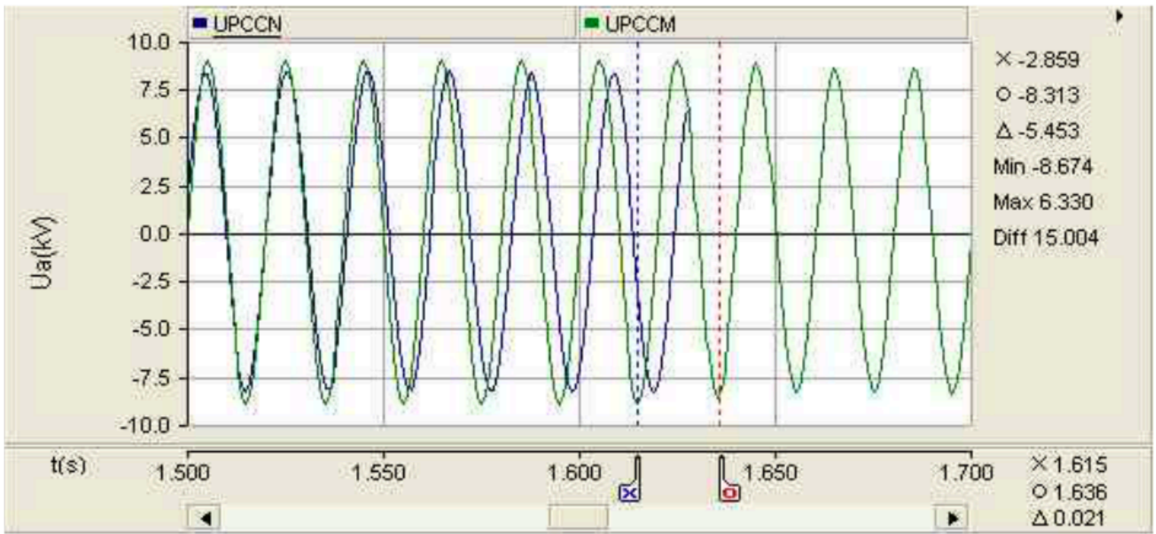

Fig 4.20 Instantaneous voltage curves on PCC switch

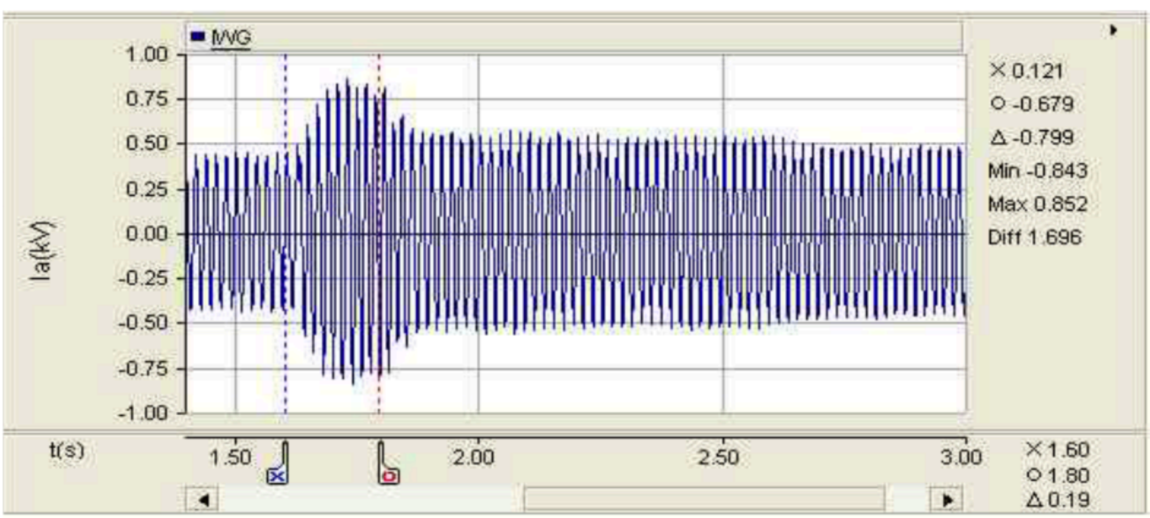

Fig 4.21 Instantaneous current curve of direct-driven wind generator

After reconnecting to utility grid, interruptible load B is operating again. The current curve of load B is shown as Fig 4.22. Sensitive load A is operating a t any time. By the time reconnecting to utility grid, there is little voltage change and large frequency change from 58 Hz to 60 Hz, which is shown in Fig 4.23 and Fig 4.24. The battery state changes from discharging to charging. As shown in Fig 4.25, the phases of AC current changes 180 degree at time t=1.63s. It means battery changes from discharging state to charging state. Fig 4.26 shows the voltage change on battery

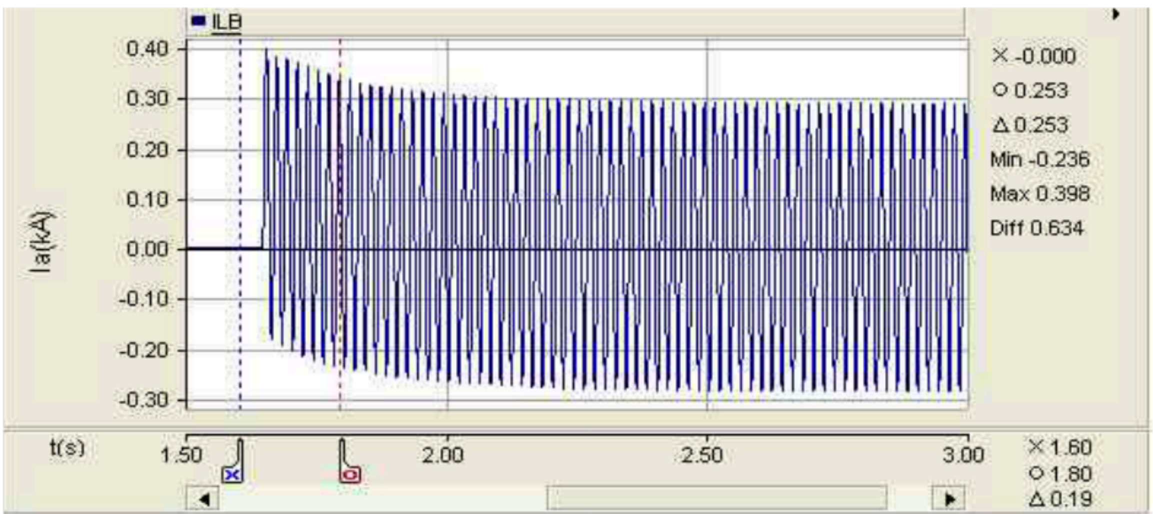

Fig 4.22 Current on interruptible load B

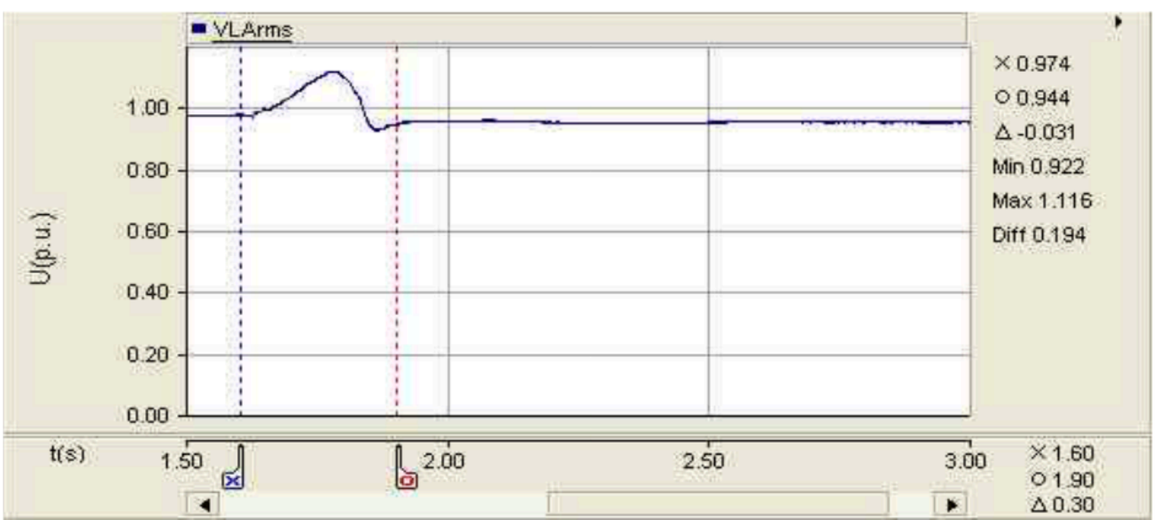

Fig 4.23 Instantaneous voltage curve on sensitive load A

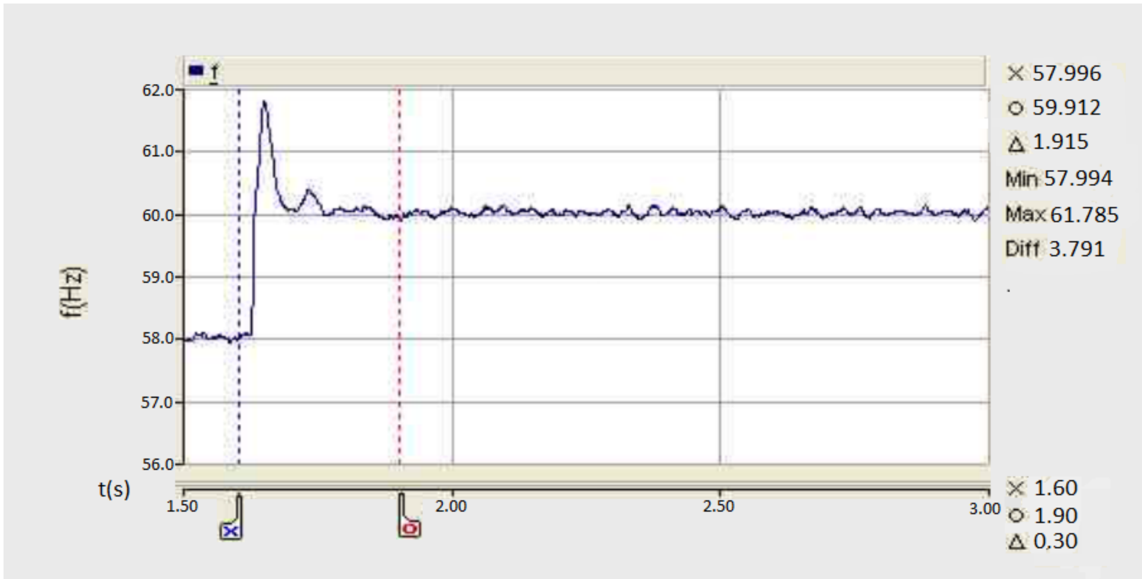

Fig 4.24 Instantaneous voltage frequency curve on load A

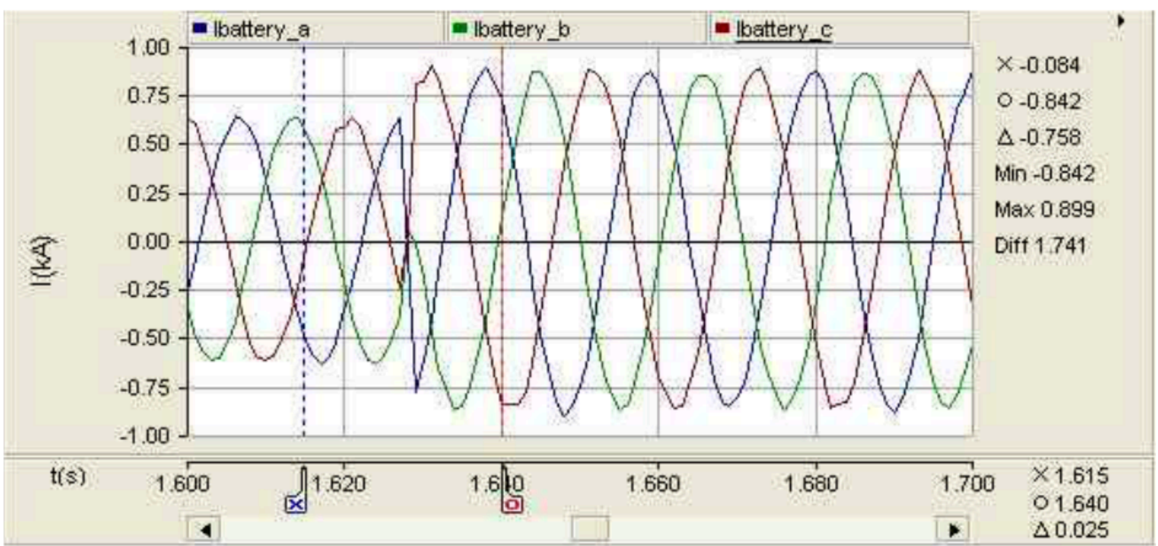

Fig 4.25 Battery three-phase current output

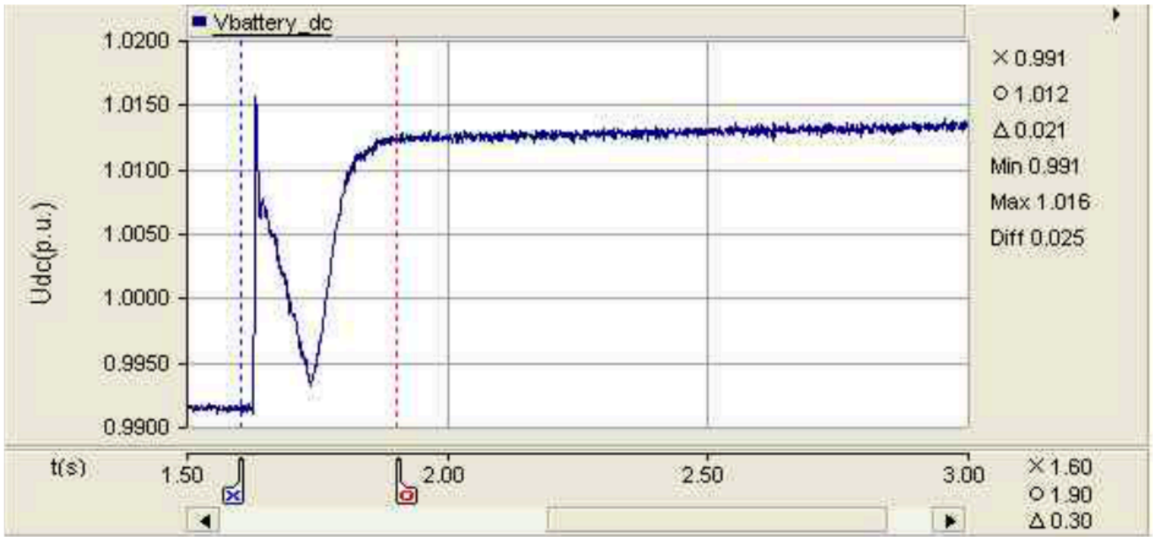

Fig 4.26 Battery voltage

This chapter uses PSCAD to set up a 'wind + storage + hydro' microgrid model. Analyzes and simulates the two typical normal operation states and three states transition.

The control system of microgrid with 'wind + storage + hydro' is to make most use of wind energy and keep the sensitive load reliable and stable. In the operation analysis, the model mainly considers the energy mutual complementation. From the simulation results, the designed control system is able to meet the load demand and ensure the reliability for local sensitive load.

CHAPTER V

CONCLUSION

The problems of utility grid, such as insecurity, unreliability and uneconomic, are increasingly prominent. The traditional fossil fuels are running out. The renewable energy technology is dominating the headlines. Developing from renewable energy technology, distributed generation becomes a necessary complement to centralized generation. Microgrid is based on distributed generation, combining distributed generation, and load to form as a whole unit. Under grid-connected mode, the power flow is dual directions. When fault occurs in utility grid, microgrid operates in island mode to supply the sensitive load. After utility grid recovery, microgrid reconnects to utility grid. There must be a suitable control strategy to control all these operations.

Due to intermittence of wind energy, to make most use of wind energy and support the sensitive load inside the microgrid, the thesis sets up a microgrid structure containing 'wind + storage + hydro', analyzes the operation states, research on control strategy based on power management and load management, coordinates the transition between different operation states, simulates the model. The main work in this thesis is listed below:

1. Different microsources need different control strategies. This thesis sets up the direct-driven wind turbine generator model, battery reserve model, and hydro generator. Direct-driven wind turbine generator uses maximum power point tracking (MPPT) control. Battery includes PQ control and Droop control. Hydro system adopts PQ control and Droop control.
2. Based on power management and load management, this thesis lists all the possible microsources combinations of 'wind +storage + hydro', and draw the corresponding state transition diagram,.
3. To make most use of wind energy and keep the sensitive load stable, this thesis illustrates 8 operation states and 24 states transition of 'wind + storage +hydro' microgrid and designs the control strategy.
4. This thesis simulates two normal operation states 'utility grid support' state and 'self support' state. Also, analyzes three state transitions from 'self support' state to 'emergency' state, from 'self support' state to 'utility support' state, and from 'emergency' state to 'wind output' state. Verifies the control strategy. Achieves the goal of fast state transition. Fulfills the demand of local sensitive load and makes most use of wind energy.

There is a hypothesis that the hydro generator capacity is large enough to support all the loads in microgrid at all time. Actually, in low water period, this hypothesis is not true. It is a further step to research on cases that hydropower is not sufficient to support all the loads. The system doesn't contain high power induction generators. This kind of generator will greatly affect the voltage and current in state transition process.

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APPENDICES

Table 1 Wind speed parameters

Mean wind	speed	6m/s
Gust wind	speed	4m/s
	period	20s
Ramping wind	highest speed	0.5m/s
	period	3s
	amplitude	3rad/s

Table 2 Wind turbine parameters

Blade radius	26.2m
Air density	1.225kg/m^3
Rated speed	2.89rad/s
Rated power	1MVA
Rated wind speed	12m/s
Maximum power coefficient	0.4382

Table 3 Synchronous generator parameters

Rated phase voltage RMS	1.1kV
Rated phase current RMS	0.30303kA
Angular frequency	121.38rad/s
Inertia constant	1.7s
Generator rated power	1MVA
Pole number	84

Table 4 Shaft parameters

Rated mechanical speed	26.814rpm
Generator power	1MVA
Electric Frequency	18.77
Wind turbine inertia constant	0.7553s
Generator inertia constant	0.3925s
Axial elastic constant	4200Nm/rad

Table 5 Hydro generator parameters

Hydro generator S_b=5MVA, V_b=13.8kV			
R_a	0.0052p.u	X_{ls}	0.02p.u
X_d	2.86p.u	X_q	2.0p.u
X_d’	0.7p.u	X_q’	0.85p.u
X_d’’	0.22p.u	X_q’’	0.2p.u

T_{do}’	3.4s	T_{do}’’	0.01s
T_{qo}’’	0.05s	H	2.9s

VITA

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